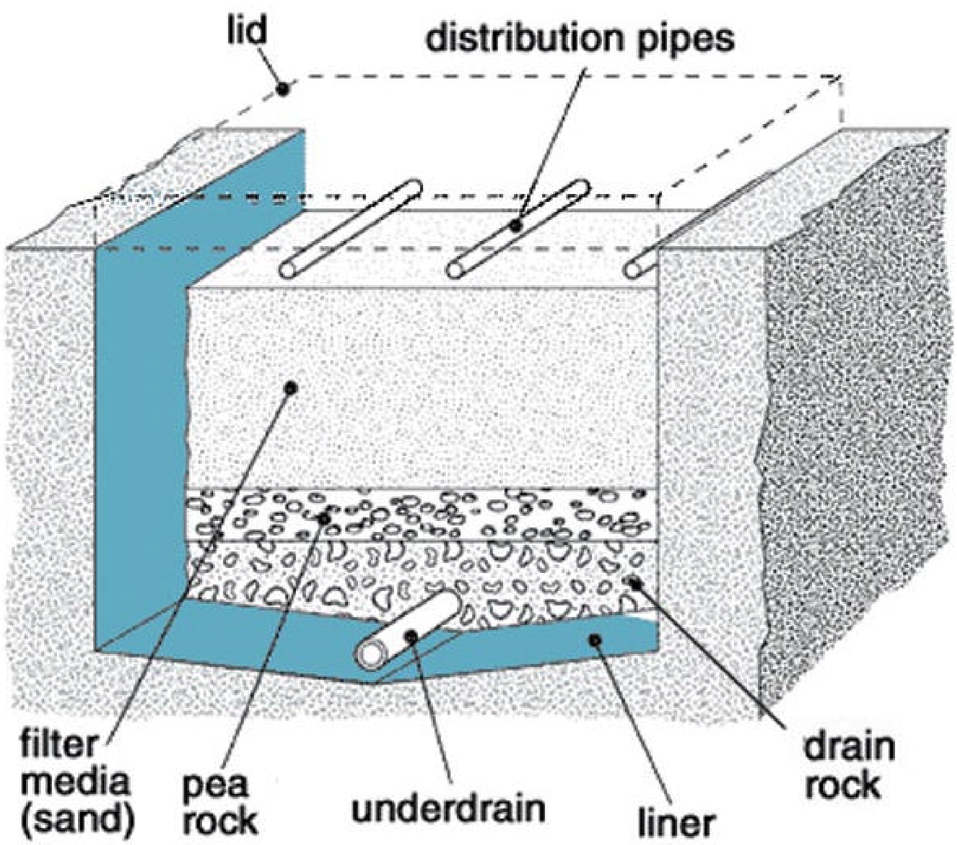
National Decentralized Water Resources
Capacity Development Project



Micro-Scale Evaluation of Phosphorus Management: Alternative Wastewater Systems Evaluation

Submitted by Stone Environmental, Inc.
Montpelier, Vermont

June 2005

Micro-Scale Evaluation of Phosphorus Management: Alternative Wastewater Systems Evaluation

Submitted by Stone Environmental, Inc. Montpelier, Vermont

NDWRCDP Project Number: **WU-HT-03-22**

National Decentralized Water Resources Capacity Development Project (NDWRCDP) Research Project

Final Report, **June 2005**

NDWRCDP, Washington University, Campus Box 1150
One Brookings Drive, Cupples 2, Rm. 11, St. Louis, MO 63130-4899

DISCLAIMER

This work was supported by the National Decentralized Water Resources Capacity Development Project (NDWRCDP) with funding provided by the U.S. Environmental Protection Agency through a Cooperative Agreement (EPA No. CR827881-01-0) with Washington University in St. Louis. This report has not been reviewed by the U.S. Environmental Protection Agency. This report has been reviewed by a panel of experts selected by the NDWRCDP. The contents of this report do not necessarily reflect the views and policies of the NDWRCDP, Washington University, or the U.S. Environmental Protection Agency, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

CITATIONS

This report was prepared by

Stone Environmental, Inc.
535 Stone Cutters Way
Montpelier, Vermont 05602

The final report was edited and produced by ProWrite Inc., Reynoldsburg, OH.

This report is available online at http://www.ndwrcdp.org/. This report is also available through the

National Small Flows Clearinghouse
P.O. Box 6064
Morgantown, WV 26506-6065
Tel: (800) 624-8301
WWCDMG45

This report should be cited in the following manner:

Etnier, C., D. Braun, A. Grenier, A. Macrellis, R. J. Miles, and T. C. White. 2005. *Micro-Scale Evaluation of Phosphorus Management: Alternative Wastewater Systems Evaluation.* Project No. WU-HT-03-22. Prepared for the National Decentralized Water Resources Capacity Development Project, Washington University, St. Louis, MO, by Stone Environmental, Inc., Montpelier, VT.

ACKNOWLEDGEMENTS

Appreciation is extended to the following individuals for assistance in the preparation of this report:

Stone Environmental, Inc.
Lesley Allen

Central Vermont Solid Waste Management District
Tom Anderson

University of Wisconsin-Madison
James C. Converse

Eco Tech
David Del Porto

Equaris ClearWater Technology
Clint Elston

NSF International
Adriana Greco

Massachusetts Alternative Septic System Test Center
George Heufelder

Lombardo Associates, Inc.
Pio Lombardo

Bohuslänskustkontroll AB
Öivind Renhammar

Jordforsk
Trond Mæhlum

Premier Tech
Eric Marcil

Simmering & Associates
Dennis G. Martin

Royal Consulting Services, Inc.
Brian Roy

Holmes and McGrath, Inc.
Timothy Santos

Solmetex
Ted Shields

Water Wastewater Maintenance Management Specialists
Jerry Stonebridge

University of Vermont
John Todd

Utelite Corporation
Jeff Barrick

Appreciation is also expressed to the NDWRCDP for their support of this work:

Principal Investigator
Jay R. Turner, D.Sc., Washington University

Project Coordinator
Andrea L. Shephard, Ph.D.

NDWRCDP Project Steering Committee:

Coalition for Alternative Wastewater Treatment
Valerie I. Nelson, Ph.D.

Consortium of Institutes for Decentralized Wastewater Treatment
Ted L. Loudon, Ph.D., P.E.

Electric Power Research Institute
Raymond A. Ehrhard, P.E.
Tom E. Yeager, P.E.

National Onsite Wastewater Recycling Association
Jean Caudill, R.S.

National Rural Electric Cooperative Association
Scott Drake, P.E.

Water Environment Research Foundation
Jeff C. Moeller, P.E.

Members-At-Large:
James F. Kreissl
Richard J. Otis, Ph.D., P.E.
Jerry Stonebridge

EXECUTIVE SUMMARY

Understanding and reducing sources of phosphorus pollution in the landscape includes evaluating and minimizing the phosphorus contribution from onsite systems to surface waters. Many phosphorus-management methods have been developed and tested for use in decentralized wastewater treatment. This project gathered information about the application, performance, cost-effectiveness, and other factors associated with each method.

A range of phosphorus-management approaches was investigated:

- **Source reduction.** Source reduction prevents phosphorus from entering wastewater streams by reducing or eliminating its use in domestic products and by reducing the amount of kitchen waste in wastewater. Source reduction results in wastewater that contains little more phosphorus than that from urine and feces.

- **Source diversion.** Two-thirds or more of the phosphorus in domestic wastewater is contained in the blackwater, and about two-thirds of the phosphorus in the blackwater is in the urine. Therefore, roughly 50% of the phosphorus generated in the home is in the urine. Collecting urine and/or feces separately, with no water or very small amounts of flush water, makes it possible to transport them cost-effectively for treatment in a less-sensitive environment or to recycle them to agriculture.

- **Precipitation in the septic tank.** If septic tank sludge is a significant sink for phosphorus, perhaps the removal potential in septic tanks could be improved.

- **Post-septic tank treatment.** A wide range of phosphorus-removal methods applied to septic tank effluent was investigated, including small-scale chemical precipitation, sequencing batch reactors, packed-bed filters, constructed wetlands, and other biotic methods.

- **Design of the soil absorption system (SAS).** Phosphorus uptake can be enhanced in the trenches or beds themselves and in the soil underneath.

- **Biotic sequestration.** Biotic sequestration spans both post-septic tank treatment and the soil absorption system. A separate investigation was made of biotic sequestration methods using other organisms than the microbial communities that naturally arise in activated sludge or attached growth secondary treatment.

Method

Representative methods in the categories identified above were identified through literature searches, conversations with practitioners, and consultation with the National Decentralized Water Resources Capacity Development Project (NDWRCDP). The most important criteria for evaluating the methods were identified as:

- Proven track record
- Phosphorus-management capability
- Cost
- System robustness
- Phosphorus-recycling capability
- Maintenance requirements
- Familiarity to the user

The seven criteria were weighted, with the highest weights awarded to cost, phosphorus-management capability, and proven track record. Each of the methods evaluated was individually scored on a scale of one to five for each of the seven criteria on this list, with five being the best. The weighted average of the scores for all criteria was then calculated for each phosphorus-management method, with 5.8 being the highest possible weighted average. The scoring was conducted transparently, with a mixture of objective measures and professional judgement. Objective measures were used for phosphorus-management capability, cost, and maintenance. All the methods were ranked according to their weighted average scores to determine the most promising phosphorus-management methods overall.

Results

Twenty-three phosphorus-management methods were evaluated (see Table 3-1). All methods were initially ranked by their overall weighted average scores. Of all the criteria used, the least amount of data was found about phosphorus-recycling capability. To anchor the evaluations more firmly in available data, the phosphorus-recycling capability was excluded from the weighted average score. The most promising phosphorus-management methods are listed in Table ES-1.

A sensitivity analysis was performed by removing each of the evaluation criteria in turn from the average score. All of the additional methods that made it into the top ten when various criteria were excluded from consideration ranked just below the top ten listed in Table ES-1; thus, the ranking is reasonably robust.

Methods that use the soil absorption system comprise five of the top ten methods. All three source-reduction strategies are among the most promising methods for phosphorus management, showing that a method does not have to eliminate large amounts of phosphorus from the waste stream to be a top scorer if it excels with respect to other criteria. Microflush toilets enable diversion of around 75% of the phosphorus in domestic wastewater to holding tanks, from which it may be treated in municipal plants or recycled in agriculture. Although lightweight aggregates were the only post-septic tank medium to rank among the most promising methods, two other methods—basic oxygen furnace (BOF) slag and PhosRid™ —show excellent potential.

Table ES-1
Most Promising Phosphorus-Management Methods Ranked by Weighted Average Score (excluding phosphorus recycling capability)

Rank	Method	Weighted Average Score Excluding P Recycling Capability
1	Comprehensive site assessment	5.3
2	Design of long, narrow trenches	5.3
3	Limestone as SAS medium	5.1
4	Phosphorus-free laundry detergent	4.9
5	Phosphorus-free dishwasher detergent	4.9
6	Shallow SAS	4.8
7	Eliminate garbage disposal	4.7
8	Lightweight aggregates	4.6
9	Microflush toilet	4.6
10	Tire chips as SAS medium	4.5

Contribution to Knowledge Base

This project collects and reviews representative portions of state-of-the-art phosphorus-management methods for decentralized wastewater systems. The approach documents the potential for phosphorus removal, reduction, and recycling, from before the beginning of the pipe (use low-phosphate detergents) to after the end of the pipe (site the soil absorption system where phosphorus uptake capability in the soil is highest). Costs of each method and benefits other than phosphorus management are also documented. Each approach to phosphorus management, from source reduction to soil absorption system design, was represented among the most promising methods, except for precipitation in the septic tank and biotic sequestration.

Source diversion methods that close the nutrient loop by recycling phosphorus from urine or blackwater to agriculture have been researched and tested in Europe in the last decade. By documenting performance of methods that use "waste" phosphorus as a resource, this project helps broaden the national discussion of phosphorus-management strategies for decentralized systems.

The research and demonstration needs documented in this project provide guidance for further developing phosphorus-management methods and demonstrating their feasibility.

Implications for Application

The method summaries presented in the report and the detailed information presented in the evaluation forms for individual methods may be useful to anyone who wants to learn more about phosphorus management in small systems, and particularly to community decision makers and members of the public who want to learn more about specific phosphorus-management methods. Watershed planners, regulators, management entities, and others can use the method summaries and ranking tables to understand the pros and cons of implementing different phosphorus-management strategies within their jurisdictions. The methods for improving soil absorption system design may be of particular interest to regulators in charge of writing rules and technical standards for onsite system design and installation.

With the exception of the source reduction strategies and some of the soil absorption system design methods, nearly all of these methods require some form of maintenance or management in order to successfully manage phosphorus in the long term. This finding has important implications for watershed managers, regulators, and management entities interested in managing phosphorus from decentralized wastewater systems.

Research and Demonstration Needs

Based on the results of this project, ten areas for research and demonstration are recognized, and the top five include:

- Demonstrate microflush toilets in terrestrial applications. (In the US, microflush toilets have been used almost exclusively on boats and ships.)
- Identify general properties of a sorbent that make it useful for phosphorus removal
- Demonstrate packed-bed filter media
- Continue developing nanoparticle selective resins
- Develop a vulnerability index for phosphorus breakthrough in soil absorption systems

TABLE OF CONTENTS

1 INTRODUCTION 1-1

1.1 Importance of Phosphorus in Aquatic Ecosystems 1-1

1.2 Contribution of Decentralized Wastewater Treatment Systems to Phosphorus in Surface Water 1-2

1.2.1 Phosphorus Generated in Homes 1-3

1.2.2 Transport of Phosphorus From Decentralized Wastewater Treatment Systems to Surface Water 1-3

1.3 Phosphorus Recycling Versus Removal 1-4

1.4 Phosphorus-Management Methods 1-4

1.4.1 Source Reduction 1-4

1.4.2 Source Diversion 1-5

1.4.3 Precipitation in the Septic Tank 1-5

1.4.4 Post-Septic Tank Treatment 1-5

1.4.5 Design of the Soil Absorption System 1-6

1.5 Methodology 1-6

1.5.1 How Methods Were Identified for Inclusion 1-6

1.5.2 How the Phosphorus-Management Methods Were Evaluated 1-7

1.5.3 How the Most Promising Methods Were Ranked 1-8

1.5.4 Quality Assurance 1-11

2 METHODS EXAMINED 2-1

2.1 Source Reduction 2-1

2.1.1 History of Phosphorus Source Reduction in the US 2-1

2.1.2 Potential for Further Phosphorus Reduction 2-2

2.1.3 Tools to Use 2-3

2.1.4 Evaluation 2-3
2.2 Source Diversion..2-6
2.2.1 History of Source Diversion...2-6
2.2.2 Potential for Phosphorus Reduction...2-7
2.2.3 Evaluation 2-22
2.3 Septic Tank..2-23
2.3.1 History of Phosphorus Management Through Septic Tanks...................................2-23
2.3.2 Phosphorus Treatment by Septic Tanks 2-25
2.3.3 Potential for Further Phosphorus Reduction 2-26
2.3.4 Evaluation of the Septic Tank and Alum Injection 2-27
2.4 Post-Septic Tank Treatment 2-28
2.4.1 Methods 2-28
2.4.2 Evaluation 2-35
2.5 Soil Absorption System...2-41
2.5.2 Potential for Further Phosphorus Removal 2-46
2.5.3 Methods 2-51
2.5.4 Evaluation 2-51
2.6 Biotic Sequestration of Phosphorus..2-56
2.6.1 History of Phosphorus Management Through Biotic Sequestration 2-56
2.6.2 Initial Screening of Phosphorus Management by Biotic Sequestration.....................2-57
2.6.3 Biotic Sequestration Evaluated in More Detail 2-57
2.6.4 Evaluation 2-62

3 MOST PROMISING PHOSPHORUS-MANAGEMENT METHODS 3-1

4 RESEARCH AND DEMONSTRATION NEEDS.. 4-1

4.1 Research and Demonstration Needs by Category 4-1
4.1.1 Source Reduction...4-1
4.1.2 Source Diversion..4-2
4.1.3 Septic Tank 4-2
4.1.4 Post-Septic Tank..4-2
4.1.5 Soil Absorption System (SAS) 4-3

4.2 Top Five Research and Demonstration Needs....4-4
4.2.1 Demonstrate Microflush Toilets in Terrestrial Applications....4-5
4.2.2 Identify General Properties of a Sorbent That Make it Useful for Phosphorus Removal....4-5
4.2.3 Demonstrate Packed-Bed Filter Media....4-5
4.2.4 Continue Developing Nanoparticle Selective Resins....4-5
4.2.5 Develop a Vulnerability Index for Phosphorus Breakthrough....4-5

5 REFERENCES....5-1

6 ACRONYMS AND ABBREVIATIONS....6-1

A TECHNOLOGY DESCRIPTION FORMS....A-1

Eliminate Garbage Disposals....A-1
Phosphorus-Free Dishwasher Detergents....A-6
Phosphorus-Free Laundry Detergents....A-11
Blackwater Diversion....A-16
Composting Toilet....A-21
Aquatron....A-27
Microflush Toilet....A-34
Infinity Water Recycling System....A-41
Urine-Diverting Toilet....A-46
Alum Injection....A-53
RUCK CFT....A-59
Lightweight Aggregates for a Packed-Bed Filter....A-66
Basic Oxygen Furnace Slag in Packed-Bed Filters....A-72
PhosRID™....A-77
Peatland™ Sewage Treatment System....A-82
Nanoparticle Selective Resin....A-89
Extended Aeration Activated Sludge....A-94
Sequencing Batch Reactor....A-100

B **DETAILED DATA TABLE USED IN BIOTA SCREENING PROCESS B-1**

LIST OF FIGURES

Figure 2-1 A Schematic of a Clivus Multrum Composting Toilet System...................... 2-9
Figure 2-2 EcoTech's Carousel.. 2-10
Figure 2-3 Sun-Mar's Self-Contained Composting Toilet, the Excel 2-10
Figure 2-4 The Aquatron Separator.. 2-12
Figure 2-5 An Example of a Plumbing System for the Aquatron 2-13
Figure 2-6 A Vacuum Toilet With the Vacuum Generator Behind the Toilet and the Holding Tank Outside the House 2-15
Figure 2-7 Infinity Water Recycling System.. 2-17
Figure 2-8 Urine-Diverting Toilets 2-19
Figure 2-9 The EcoTrap® Used in the No-Flush™ Urinal 2-20
Figure 2-10 A Septic Tank and Its Parts.. 2-24
Figure 2-11 Example of a Sand Filter... 2-29
Figure 2-12 Schematic Diagram of a RUCK CFT System... 2-30
Figure 2-13 An Example of the Mechanism of Phosphorus Adsorption When an Effluent Orthophosphate is Bonded Through One Al-O-P Bond Providing Labile P 2-43
Figure 2-14 Relative Phosphorus Fixation With pH.. 2-44
Figure 2-15 Leachfield Trenches (upper) and a Leachbed (lower) for Distributing Effluent.. 2-48
Figure A-1 A Vacuum Toilet With the Vacuum Generator Behind the Toilet and the Holding Tank Outside the House A-35
Figure A-2 Traditional RUCK..A-65
Figure A-3 RUCK CFT A-65

LIST OF TABLES

Table 1-1 Weighting of Criteria 1-9
Table 1-2 Evaluation System Used for Phosphorus-Management Capability 1-9
Table 1-3 Evaluation System Used for Cost 1-10
Table 1-4 Evaluation System Used for Maintenance 1-11
Table 2-1 Evaluation of Eliminating Garbage Disposals 2-4
Table 2-2 Evaluation of Phosphorus-Free Laundry Detergents 2-5
Table 2-3 Evaluation of Phosphorus-Free Dishwasher Detergents 2-5
Table 2-4 Composition and Volume of Domestic Wastewater, Annual per Capita Amounts 2-7
Table 2-5 Evaluation of Composting Toilets 2-11
Table 2-6 Evaluation of Aquatron 2-14
Table 2-7 Evaluation of Microflush Toilets 2-17
Table 2-8 Evaluation of Equaris Infinity Water Recycling System 2-18
Table 2-9 Evaluation of Urine Diversion 2-22
Table 2-10 Evaluation of a Technology for Alum Injection 2-27
Table 2-11 Evaluation of RUCK CFT 2-36
Table 2-12 Evaluation of PhosRID™ 2-37
Table 2-13 Evaluation of Lightweight Aggregates in Packed-Bed Filters 2-37
Table 2-14 Evaluation of Basic Oxygen Furnace (BOF) Slag in Packed-Bed Filters 2-38
Table 2-15 Evaluation of Peatland™ System 2-39
Table 2-16 Evaluation of Nanoparticle Selective Resin 2-39
Table 2-17 Evaluation of Extended-Aeration Activated Sludge 2-40
Table 2-18 Evaluation of Sequencing Batch Reactor 2-41
Table 2-19 An Example of a Table Assigning Points in the Field to Some Soil Morphological Site Characteristics That Affect Phosphorus Removal 2-47
Table 2-20 Evaluation of Comprehensive Site Assessment 2-52
Table 2-21 Evaluation of Added Materials in SAS for “Doping” 2-52
Table 2-22 Evaluation of Timed, Pressure Dosing With Drip Distribution 2-53
Table 2-23 Evaluation of Design of Long, Narrow Trenches With Effluent Directed to a Trench to Pond It 2-54

Table 2-24 Evaluation of Narrow, Shallow SAS 2-54
Table 2-25 Evaluation of Replacement of Gravel in Trench With Tire Chips............. 2-55
Table 2-26 Evaluation of Replacement of Gravel in Trench With Limestone 2-55
Table 2-27 Summary of Plant Species and Biotic Communities With Greatest Phosphorus-Removal Potential 2-58
Table 2-28 Evaluation of Periphyton 2-62
Table 2-29 Evaluation of Duckweed.. 2-62
Table 2-30 Evaluation of Water Hyacinth 2-63
Table 2-31 Evaluation of Cattail 2-64
Table 3-1 Phosphorus-Management Methods (excluding biota) Ranked by Weighted Average Score 3-2
Table 3-2 Phosphorus-Management Methods (excluding biota) Ranked by Weighted Average Score Excluding Phosphorus-Recycling Capability 3-3
Table 3-3 Methods Not in the Top Eleven of Table 3-2 but Which Rank in the Top Ten When Other Criteria Are Excluded 3-4
Table 3-4 Phosphorus-Management Methods (excluding biota) Ranked by Phosphorus-Management Capability 3-7
Table A-1 Calculation of Phosphorus-Removal Potential for Phosphorus-Free Dishwasher Detergents A-8
Table A-2 Calculation of Historic Improvements Gained by Implementing Phosphorus Removal for Household Laundry Detergents A-13
Table A-3 Swedish Standard Values for Heavy Metal Content in Feces A-31
Table A-4 Heavy Metal Content in Feces and Composted Feces Compared With Limits for US EPA's EQ Sludge and EPA's Ceiling for Land-Applied Sludge...... A-31
Table A-5 Heavy Metal Content in Urine Compared With Limits for US EPA's EQ Sludge and EPA's Ceiling for Land-Applied Sludge A-50
Table B-1 Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential B-2

1 INTRODUCTION

1.1 Importance of Phosphorus in Aquatic Ecosystems

In the 2000 National Water Quality Inventory (US EPA 2002), nutrient enrichment is identified as a leading cause of water-quality impairment in surveyed waters of the US. Pollution of surface waters with nutrients accelerates eutrophication, which is the process by which the biological productivity of water bodies increases in response to increased nutrient concentrations (Vollenweider 1968; Horne and Goldman 1994).

In temperate regions, phosphorus (P) is the nutrient primarily responsible for accelerating eutrophication of freshwaters, because phosphorus is usually in limited supply relative to plant demand (Schindler 1977; Hecky and Kilham 1988). Plants require phosphorus for the synthesis of genetic material, phospholipid membranes, and compounds essential to metabolism (Wetzel 1983). Several factors result in low concentrations of phosphorus in temperate freshwaters relative to other potentially limiting nutrients. Phosphorus has no common gaseous form, whereas carbon and nitrogen gases in the atmosphere dissolve in surface waters and become fixed by photosynthetic and nitrogen fixing organisms (Schindler 1977; Levine and Schindler 1989). In addition, the affinity of phosphorus for the particulate phase results in rapid sedimentation of phosphorus from the water column. Given the relative scarcity of phosphorus in aquatic systems, rates of biological production tend to be balanced with inputs of phosphorus.

In eutrophying rivers, lakes, and wetlands, an increase in dissolved, biologically available phosphorus causes increased production of algae and higher aquatic plants (Ryding and Rast 1989). As aquatic systems become eutrophic, there are shifts in the aquatic food web structure and the species composition of fish, plant, microbe, and invertebrate communities (Tilman *et al.* 1982; Pace and Funke 1991). Algal blooms may become frequent, fish kills may occur due to dissolved oxygen depletion, and exotic species often proliferate (Cooke *et al.* 1993). Physico-chemical characteristics associated with eutrophication include reduced water clarity, increased sedimentation, and dissolved oxygen depletion in the water column and sediments. Eutrophic water bodies may produce noxious odors, unpalatable drinking waters, and toxic algal blooms (Cooke *et al.* 1993; Ryding and Rast 1989). Higher levels of trihalomethanes, potentially carcinogenic byproducts of chlorine disinfection, have been reported in drinking water when source waters are eutrophic (Palmstrom *et al.* 1988). This deterioration in water quality limits recreational and water supply uses of surface waters (Sharpley *et al.* 1994; US EPA 2002).

Management of lake eutrophication in North America and Europe is based on controlling phosphorus loading (Hecky and Kilham 1988; Carpenter *et al.* 1995). Wastewater inputs are a major source of phosphorus pollution in aquatic ecosystems. Since passage of the Clean Water Act in the US in 1972, there has been considerable focus on reduction of phosphorus levels in effluent from public wastewater treatment plants in the US; however, the evaluation of the environmental impacts of onsite wastewater treatment systems has received much less attention. The contribution of onsite wastewater treatment systems to phosphorus loads at the watershed scale is difficult to measure. Based on the strong affinity of soils for phosphorus, phosphorus loading to surface waters from functioning conventional onsite systems is often assumed to be minimal. However, a growing body of research challenges the assumption that conventional onsite systems relying on a septic tank and soil absorption system (SAS) for phosphorus management are adequate to prevent impairment of surface waters in the long term (see section 1.2.2).

Understanding and managing sources of phosphorus pollution in the landscape necessitate evaluating and minimizing the phosphorus contribution from onsite systems to surface waters. This handbook describes the nature of the problem and synthesizes recent research to elucidate how different treatment options affect the risk of phosphorus pollution from onsite systems.

1.2 Contribution of Decentralized Wastewater Treatment Systems to Phosphorus in Surface Water

Conventional onsite wastewater treatment systems are gravity-flow systems consisting of a septic tank, a distribution box, and a subsurface soil absorption area to treat and disperse effluent in the subsurface soil. As effluent from the septic tank percolates into the soil, phosphorus is removed through a variety of chemical reactions in the soil. Adsorption and precipitation reactions occur for a period that may effectively retain wastewater phosphorus in the soils without leaching to the water table aquifer (Gold and Sims 2000). Phosphorus is adsorbed to soils by reaction with clay minerals, aluminum and iron oxyhydroxides, manganese, and calcium carbonate. Phosphorus is precipitated in a relatively insoluble mineral phase through reaction with metal ions contained in the effluent and the soil such as aluminum, manganese, calcium, and iron. Soils differ in their capacity to complex phosphorus based on their composition and structure. Fine-textured soils generally have a higher sorption capacity for phosphorus than sands. The sorption capacity of all soils is, however, finite; when the reactions that complex phosphorus in the soil reach equilibrium, phosphorus will migrate further toward groundwater or surface water receptors.

The efficiency of phosphorus retention in conventional soil absorption systems is dependent on a host of factors related to the system design, use, and maintenance, as well as to characteristics of the effluent dispersal site. These factors are a critical area of research. Three broad categories of factors affecting the fate and transport of phosphorus from onsite systems are:

1. Characteristics of the wastewater stream—the rate and timing of the wastewater flow and its chemical composition, particularly its phosphorus and major cation concentrations.

2. Site characteristics, including soil properties that affect the retention and release of phosphorus, hydraulic conductivity of the vadose zone and aquifer materials, water table elevations and fluctuations relative to the dispersal units, and proximity of the SAS to surface

waters. Site conditions that create short, predominantly lateral flow paths increase the potential for significant phosphorus loading to adjacent surface waters.

3. System design and maintenance, particularly the uniformity of wastewater distribution to the SAS and the regularity of septage pumping. Uniformly distributing wastewater takes advantage of the full volume of soils in the vadose zone for phosphorus complexing reactions, resulting in lower phosphorus loss to groundwater than non-uniform distribution systems (Gold and Sims 2000).

1.2.1 Phosphorus Generated in Homes

Phosphorus is contained in urine, feces, food wastes, and some household products. The average individual contributes 2.0 – 4.5 grams per person, per day (g/person/day) to wastewater (Vinnerås, Submitted; Crites and Tchobanoglous 1998).

1.2.2 Transport of Phosphorus From Decentralized Wastewater Treatment Systems to Surface Water

Under certain conditions, significant quantities of phosphorus have been demonstrated to escape to water bodies from onsite systems. Bicki *et al.* (1984) attribute most cases of surface water contamination with phosphorus from onsite systems to adverse site conditions: systems that are located proximate to surface waters or where drainage tile or drainage ditches intercept groundwater before soil treatment is complete. Site conditions that create short, predominantly lateral flow paths—such as high water tables and restrictive layers underlying shallow, coarse-textured soils—increase the potential for significant phosphorus loading to adjacent surface waters.

Poorly designed, maintained, or sited systems may pose an immediate risk to human health and adjacent surface waters. The principal pathways for phosphorus transport from onsite systems to surface waters are through surfacing of wastewater resulting from system failure and through shallow groundwater flow (Gold and Sims 2000). Surfacing septic tank effluent presents risks to the environment and human health beyond phosphorus pollution; failed systems result from exceptionally poor design, maintenance, and/or siting. Systems that appear to function properly may nonetheless pose an increased risk to the environment as they age, due to exhaustion of the phosphorus-sorption capacity of the soils overlying the water table and subsequent transport of phosphorus to receiving waters in shallow groundwater flow.

In an investigation of ten "mature" septic systems, Robertson *et al.* (1998) found that phosphorus retention in the vadose zone ranged from 23 to 99%. From the standpoint of phosphorus transport, the system that was only able to retain 23% of the wastewater phosphorus has clearly outlived its useful life, while the system retaining 99% may still be functioning optimally. A better understanding of the factors affecting phosphorus transport from onsite systems may enable predictions of the lifespan of different system designs in different hydrologic and geochemical settings (including soil type).

1.3 Phosphorus Recycling Versus Removal

An aspect of phosphorus management that is receiving increased attention is the potential for phosphorus recovery from wastewater (*Phosphates: A Sustainable Future in Recycling* 1998; *Recovery of Phosphates for Recycling* 1998). The traditional phosphorus cycle, where phosphorus in agricultural fields is used to produce crops consumed by humans and livestock and is recycled back to the land in manure, no longer operates in many developed areas of the world. The cycle has been largely replaced by a linear, throughput system, where phosphorus for agricultural and industrial use is mined from non-renewable deposits of phosphate rock, and phosphorus in human animal wastes is managed as a pollutant as opposed to a resource. In rural areas where land application of animal and livestock wastes is still a viable option, this practice is a cost-effective form of phosphorus recycling. In more developed areas where direct application of wastes is not feasible, there are now technologies available that can recover 50 to 80% of the phosphorus from wastewater in a usable form for agriculture and industry (*Recovery of Phosphates for Recycling* 1998).

Nutrient recycling is the motivation behind much of the European work on the methods examined in Section 2.2 (for example, Skjelhaugen 1999; Höglund 2001; Vinnerås 2002).

1.4 Phosphorus-Management Methods

In keeping with the “soft path” approach to wastewater treatment (Nelson 2003), which uses a variety of different means to achieve a given end most efficiently, a range of phosphorus-management approaches, from source reduction to soil absorption system design, was examined.

Phosphorus-management approaches examined include:

- Source reduction
- Source diversion
- Precipitation in the septic tank
- Post-septic tank treatment
- Design of the soil absorption system

1.4.1 Source Reduction

Source reduction prevents phosphorus from entering wastewater streams by reducing or eliminating its use in domestic products and by reducing the amount of kitchen waste in wastewater. Source reduction results in wastewater that contains little more phosphorus than that from urine and feces.

1.4.2 Source Diversion

Two-thirds or more of the phosphorus from domestic wastewater is contained in the blackwater, and about two-thirds of the phosphorus in the blackwater is in the urine. Therefore, roughly 50% of the phosphorus generated in the home is in the urine. (The distribution of phosphorus in domestic waste streams is discussed in detail in section 2.2.) Three types of source diversion methods were investigated:

1) Holding tanks for blackwater and separate treatment of graywater, used with toilets with 1.0 L water per flush or less.

2) Composting of feces and separate treatment of graywater.

3) “No-mix” toilets, which keep urine separate from feces. With these toilets, quantities of blackwater or so-called yellowwater (urine plus flush water) can be kept small.

Trucking the small amounts off site for treatment in less-sensitive areas or even for nutrient recycling to agriculture is much more attractive than with conventional fixtures and holding tanks.

1.4.3 Precipitation in the Septic Tank

If septic tank sludge is a significant sink for phosphorus, perhaps the removal potential in septic tanks could be improved.

1.4.4 Post-Septic Tank Treatment

A wide range of phosphorus-removal methods has been applied to septic tank effluent, including

- Small-scale chemical precipitation
- Sequencing batch reactors
- Packed-bed filters
- Constructed wetlands
- Other biotic methods

Representative methods from each of these areas were examined, including numerous materials for packed-bed filters.

1.4.5 Design of the Soil Absorption System

Phosphorus uptake can be enhanced in the trenches or beds themselves and in the soil underneath.

1.5 Methodology

1.5.1 How Methods Were Identified for Inclusion

Representative methods in the categories identified above have been identified through literature searches, conversations with practitioners, and consultation with the client: members of the Subcommittee on Environmental Science and Engineering for the National Decentralized Water Resources Capacity Development Project (NDWRCDP).

This section describes the means used to identify phosphorus-management methods for each category.

1.5.1.1 Source Reduction

Reducing phosphate levels in laundry detergents and dishwasher detergents, plus handling organic kitchen wastes through some method other than a garbage grinder, are the source reduction methods that the research team was aware of before starting the project. No further search was conducted.

1.5.1.2 Source Diversion

One of the authors has been involved with source diversion in the countries where it has received a great deal of attention (Sweden, Norway, Germany, and Switzerland) since the early 1990s. This author's related activities include organizing (Etnier and Guterstam 1997; Staudenmann *et al.* 1996) and attending international conferences that address the subject, translating some of the literature into English (for example, Ridderstolpe 1999), publishing evaluations of the systems (Etnier *et al.* 1997; Refsgaard and Etnier 1998; Etnier and Refsgaard 1998), and editing a newsletter (*EcoEng*), which regularly publishes new information on source diversion. His contacts were used to identify the latest research results in source diversion.

1.5.1.3 Precipitation in the Septic Tank

Standard wastewater literature was consulted, along with references from Gold and Sims (2000), and a limited additional literature review was performed. The initial data examined showed so little promise for using primary treatment in the septic tank as a method for removing significant amounts of phosphorus that a more extensive literature review was not carried out; only around five percent reduction was generally found.

1.5.1.4 Post-Septic Tank Treatment

The focus for this category was on methods that did not produce large amounts of sludge to be hauled away. Methods were identified through a review of papers presented at recent conferences and trade shows—National Onsite Wastewater Recycling Association (NOWRA) and American Society of Agricultural Engineers (ASAE)—and conversations with directors of test centers like NSF International (Tom Bruursema) and the Massachusetts Alternative Septic System Test Center (MASSTC) (George Heufelder). These sources were complemented by selective Internet searches to follow up on specific types of methods. Inquiries with leading onsite wastewater researchers in Sweden and Norway were used to identify the recent Scandinavian literature.

1.5.1.5 Design of the Soil Absorption System

One of the authors has great familiarity with the methods of phosphorus uptake in soils through his research and teaching at the University of Missouri, as Director of the Missouri Wastewater Small Flows Research/Training Center, and as Director of Historical Sanborn Field, which is the third oldest continuous research field in the world. He has also published numerous papers (Miles 1998; Miles and West 2001) on soil evaluation and onsite wastewater treatment systems. His overview of the literature, augmented by a limited additional literature search, was used to identify ways to improve treatment in the soil absorption system. The methods identified also built on the work of Gold and Sims (2000).

1.5.1.6 Biotic Sequestration

Biotic sequestration spans both post-septic tank treatment and the soil absorption system. A separate investigation was made of biotic sequestration methods using organisms other than the microbial communities that naturally arise in activated sludge or attached growth secondary treatment. These methods, which are placed between the septic tank and the SAS or are a part of the SAS, were identified through a literature search using ISI Web of Science and other journal databases. In addition, a researcher who has decades of experience using biotic methods to treat wastewater (Todd 1986; Todd 1996; Todd *et al.* 2000; Todd 2000) canvassed his colleagues around the world to assess what they know about biotic methods for phosphorus management.

1.5.2 How the Phosphorus-Management Methods Were Evaluated

Phosphorus-management methods were evaluated according to the following criteria:

- **Phosphorus-management capability.** Does the method substantially reduce the phosphorus in the effluent?
- **Cost.** What are the costs for the installed system and the life-cycle costs over thirty years?

- **Phosphorus-recycling capability.** Is the phosphorus removed from the wastewater in a form that facilitates recycling to agriculture? (Recycling capability applies only to that phosphorus which is removed from the wastewater; a method may have a low capture rate but high recycling capability.)
- **Robustness of the system.** Can the system reliably remove phosphorus in a variety of wastewater loading situations (high/low volume/strength) and/or handle surges in loading, as with homes occupied on weekends only?
- **Maintenance requirements.** How frequently is maintenance required and how difficult is the maintenance?
- **Proven track record.** Has this method been used over the years and is it consistent in its performance?
- **Impact on landscape.** Does the method have a small or large footprint? Is it too intrusive or aesthetically unpleasant?
- **Energy requirements.** Does the system require a large or small energy input on a continuous or periodic basis?
- **Site limitations.** Is the method limited by soils or other site considerations?
- **Familiarity to the user.** Does the method require toilets that are not in standard use, for example, composting toilets or no-mix (urine-diverting) toilets?

Where feasible, the evaluations were performed using standardized evaluation forms (Appendix A). The sections on the septic tank, the soil absorption system, and biotic methods do not include specific products, so they were written directly in a literature review format, without evaluation forms.

This report focuses on options that work technically, with consideration of the role of the user in the technical system. No attempt was made to investigate where the options may be permitted by wastewater regulations. It is up to the regulatory community to decide which of these options to permit in their jurisdictions.

1.5.3 How the Most Promising Methods Were Ranked

To determine the most significant of the ten criteria above, two of the authors independently rated the importance of the criteria. Input was also received at a meeting of people working on water-quality issues for phosphorus-sensitive Table Rock Lake, Missouri. The meeting was attended by state regulators, a retired civil environmental engineer, the head of Table Rock Water Quality, Inc. (TRWQ), and three local citizens who serve on the TRWQ board. The list was expanded in discussion with the NDWRCDP. Finally, the criteria were given the following weights:

Table 1-1
Weighting of Criteria

Criterion	Weight
Proven track record	1.3
Phosphorus-management capability	1.3
Cost	1.4
Robustness of system	1.0
Phosphorus-recycling capability	1.0
Maintenance requirements	1.1
Familiarity to the user	1.0

Each of the methods evaluated was scored on a scale of one to five for each of the criteria on this list, with five being the best. The weighted average of the scores for all criteria was calculated for each phosphorus-management method. The highest attainable weighted average score using the weights in Table 1-1 is 5.8.

The scoring was done with a mixture of objective measures and professional judgement. Objective measures were used for phosphorus-management capability, cost, and maintenance.

Phosphorus-management capability was rated using the system in Table 1-2. Methods for which management capability varied across the categories were rated according to their capability when functioning best. For example, package treatment units with chemical dosing were rated according to removal when dosing functions as designed, even if field performance shows that dosing varies. Variations in management capability are reflected in the criteria of robustness and maintenance requirements.

Table 1-2
Evaluation System Used for Phosphorus-Management Capability

Percentage Phosphorus Removed	Points
81–100	5
61–80	4
41–60	3
21–40	2
0–20	1

Costing begins from a baseline system consisting of conventional plumbing and fixtures, a septic tank, and a soil absorption system. A method that has no additional cost starts out with a point value of 5. If a method costs more than that, for installation plus ongoing maintenance, then points were subtracted according to Table 1-3. For example, a system that costs $7,000 more to install than the baseline system and has no additional maintenance requirements receives a rating of 5-2=3. Life-cycle costs were calculated over a 30-year lifetime. A publication of results from a computer program that assists users in computing *C*osts of *O*n*S*ite *M*anagement *O*ptions (COSMO), was used as a guide (Hoover 1997). For example, the discount rate COSMO uses for future operation and maintenance (O&M) expenditures was used in the life-cycle cost (net present value) calculations. Where costs for a phosphorus-management method or its O&M were not directly obtained, estimates were constructed using costs from COSMO. The cost estimates used from COSMO were updated to account for inflation since 1997 and verified in a discussion with Jerry Stonebridge, who is an onsite system installer and maintainer.

Table 1-3
Evaluation System Used for Cost

Added Life-Cycle Cost ($)	Points (Subtracted From 5)
1–5,000	– 1
5,000–10,000	– 2
10,000–15,000	– 3
15,000+	– 4

For maintenance, the baseline system was again given a score of 5. Points were subtracted for different amounts of maintenance, according to Table 1-4. For example, a system that requires a major component to be replaced every three years, plus chemical addition every week, would get a 5-2-1=2 for a score.

The other scores were more subjective. Comments for each score show why the authors chose that score. The intention was to be completely transparent about the rating system, so that the reader could repeat the scoring and change those scores that he or she disagrees with. The tables with the scores for the different methods are included in each section.

Table 1-4
Evaluation System Used for Maintenance

Major Component Replacement	
Interval	**Points (Subtracted from 5)**
Every 0–2 years	– 3
Every 2–5 years	– 2
Every 5–10 years	– 1
Every 10 + years	0
Major Visits (Septage Pumping, More Than Just Simple Water-Quality Monitoring, Not Including Component Replacement)	
Interval	**Points (Subtracted from 5)**
2+ times per year	– 3
Every 1–3 years	– 2
Every 3+ years	0
Minor Visits (Such as Routine Refilling of Chemical)	
Interval	**Points (Subtracted From 5)**
Monthly or more	– 1
Monthly or less	0

Based on these scores and the weighting factors above, a weighted average was calculated for each method. For those methods for which one or more criteria were not scored, the weighted average was based on the criteria that were scored, and the weighted average was marked with one or more asterisks to indicate that it was based on incomplete scoring.

1.5.4 Quality Assurance

This project used only secondary data; the project team collected no new measurements. To ensure that quality objectives were met, a Quality Assurance Project Plan (QAPP) was written and followed for this project (Stone Environmental 2004). Evaluations of key secondary data sets for phosphorus-management methods are documented in Etnier *et al.* (2005).

2 METHODS EXAMINED

2.1 Source Reduction

Several methods for reducing the amount of phosphorus (P) that enters decentralized wastewater systems were investigated, including the use of phosphorus-free laundry detergents, the use of phosphorus-free dishwashing detergents, and the elimination of household in-sink garbage disposals. Sources examined in this section of the report included government reports; peer-reviewed papers; websites of watershed, lake, and river associations; and professional e-mail listservs.

2.1.1 History of Phosphorus Source Reduction in the US

Powdered laundry detergents that were developed for washing machines after World War II contained high levels of sodium tripolyphosphate (as much as 60% by weight, or about 15% by weight as phosphorus) as a builder (Litke 1999). Builders neutralize hardness in water so that the surfactants in the detergent can function. The use of phosphorus in synthetic detergents peaked in 1967 at 220,000 metric tons (US Congress 1970). The detergent industry in the US voluntarily agreed to limit phosphorus in detergents to 8.7% by weight in 1970 (Litke 1999). Although no federal legislation restricting phosphorus levels was passed, many states introduced total or partial bans on phosphorus in laundry detergents in the 1970s and 1980s as part of their response to increasingly eutrophic surface water conditions, particularly in eastern coastal areas and in the Great Lakes states. These bans typically restricted phosphorus levels in laundry detergents to 0.5% or less by weight. The reduction of phosphorus content in laundry detergents from 8.7% phosphorus by weight to 0.5% or less resulted in an average wastewater influent phosphorus reduction of 59% (2.4 g/person/day) (US EPA 2002).

A total of 27 states and the District of Columbia introduced total or partial bans on phosphorus in laundry detergents between 1970 and 1995 as part of their response to increasingly eutrophic surface water conditions. These bans, however, did not extend to dishwashing detergents (Litke 1999; Jones and Hubbard 1986). In many cases, a limit of 8.7% phosphorus by weight was instituted for dishwashing detergents and other household cleaning agents (Jones and Hubbard 1986). Now that automatic dishwashers are common fixtures in American households, several states (most notably Massachusetts, Michigan, and Minnesota) are considering extending the phosphorus ban to include household dishwashing detergents. Several phosphorus-free automatic dishwashing detergents are already on the market, although they generally cost more than mainstream detergents.

Household garbage disposals, or garbage grinders, shred food scraps, vegetable peelings and cuttings, bones, and other food wastes, allowing them to flow into the wastewater treatment system (US EPA 2002). For any onsite system, the installation of a garbage disposal causes faster buildup of scum and sludge layers in a septic tank and increased risk of organic overloading in the soil absorption system (SAS) due to higher total suspended solids (TSS) concentrations in the effluent (US EPA 2002). Although the primary concern with garbage disposals involves increased biological oxygen demand (BOD), which is a measure of organic matter, and TSS loadings, they also increase total phosphorus loadings by 2 to 10%, or approximately 0.16 g/person/day (US EPA 2002). Eliminating garbage disposals not only reduces the amount of phosphorus entering the system, but also improves system performance by reducing organic loadings, pumping frequencies, and the risk of premature system failure. Some other provision does need to be made for the kitchen waste, such as on-lot composting or curbside pickup for composting.

2.1.2 Potential for Further Phosphorus Reduction

Although it is generally agreed that the industry phased out the use of phosphorus in domestic laundry detergents by about 1994 (Litke 1999), Rohrer (1999) reports that states with phosphorus bans still had problems in the early 1990s with high-phosphorus laundry detergents being sold, and enforcement efforts were still necessary. No indication has been found that laundry detergent is a significant source of phosphorus in domestic wastewater today, but there does not seem to be much enforcement activity. The state bans and eventual nationwide phase-out of phosphorus in laundry detergent are a success story for phosphorus management using source reduction. Preventing the re-emergence of phosphorus-containing laundry detergents represents the greatest potential for this method of source reduction. Since the US is increasingly importing products from countries with less strict environmental rules and there is little evidence of enforcement of phosphorus bans, it is conceivable that present gains might be rolled back without being detected.

In the early 1970s, when phosphorus limits for laundry detergent were set, automatic dishwashers were relatively uncommon and there was not a perceived need to severely limit or ban phosphorus in dishwashing detergents. Now that dishwashers are common in many homes, efforts are underway in several states to ban phosphorus in dishwashing detergents as well (Rohrer 1999; Stucky 2003; Tip of the Mitt Watershed Council 2000; Organization for the Assabet River 2003). Restrictions on the phosphorus content of dishwashing detergent similar to those for laundry detergent, limiting phosphorus content to 0.5% or less by weight, would result in an average wastewater influent phosphorus reduction of 23% (0.61 g/person/day) (US EPA 2002). The universal use of phosphorus-free dishwashing detergent would reduce phosphorus in the waste stream by only an additional 1% (0.04 g/person/day).

Not installing garbage disposals in new construction or during remodeling has the potential to reduce the phosphorus load by 0.05 to 0.27 g/person/day, or 2 to 10% of the typical domestic phosphorus load. The same reduction would be possible by removing or incapacitating garbage disposals where they exist. Not installing a garbage disposal represents a cost savings, while removing or incapacitating an existing garbage disposal may cost money and/or causes an alteration in the user's habits that the user may be unwilling to make. The do-not-install option only was evaluated under this project.

2.1.3 Tools to Use

Most of the methods available to reduce the amounts of phosphorus entering onsite systems are regulatory- and policy-related tools. In addition to the existing state laws restricting the phosphorus content of laundry detergents, any of the following tools could prove effective:

- Federal legislation limiting or banning phosphorus in laundry detergents
- State or federal legislation limiting or banning phosphorus in dishwashing detergents and other cleaning agents
- Limiting or banning phosphorus in commercial/industrial cleaners and detergents
- Incentive or discount programs encouraging consumers to purchase phosphorus-free detergents and cleaners

To avoid new garbage disposals, the following tools may be used:

- Banning new garbage disposals anywhere in a jurisdiction, using wastewater ordinances or plumbing codes
- Attaching a ban on garbage disposals for specific residences to deeds and/or to revocable onsite wastewater treatment system operating permits (EPA management level 3, US EPA 2003)
- Instituting a pick-up and composting service for household organic waste (particularly important in urban areas where onsite composting is more challenging)

2.1.4 Evaluation

Table 2-1, Table 2-2, and Table 2-3 indicate how the team scored the methods evaluated. An explanation of the scoring is in section 1.5.2.

The most important data sources used for research on eliminating garbage disposals, phosphorus-free laundry detergents, and phosphorus-free dishwasher detergents were all given a High confidence-level rating, using the scale developed as part of this project's Quality Assurance Project Plan (QAPP) (Etnier *et al.* 2005).

Table 2-1
Evaluation of Eliminating Garbage Disposals

Criterion	Score	Comment
Proven track record	5	Designers/regulators have been aware of increased P from garbage disposals since the 1950s, and households have disposed of organic waste without garbage disposals for millennia.
Phosphorus-management capability	1	Removal of garbage disposals results in a decrease of only 2 to 10% of the total average loading.
Cost	3–5	Not installing a garbage disposal creates no additional construction cost to the system, and may actually save money because less septic tank capacity is necessary and the garbage disposal costs money. Where composting on site is difficult to implement, a family of four may spend $500/year for curbside compost pickup.
Robustness of system	5	The alternative can be used on any system, regardless of design flow, application, or climate.
Phosphorus-recycling capability	5	If kitchen waste is composted, its P is easily available for plant uptake.
Maintenance requirements	5	None.
Familiarity to the user	3	In order to compost kitchen waste, the user must separate waste streams and maintain a compost pile (if municipal pickup is not an option).
Weighted Score	4.4 – 4.8	

Table 2-2
Evaluation of Phosphorus-Free Laundry Detergents

Criterion	Score	Comment
Proven track record	5	Used in households since the 1970s. Millions of containers sold.
Phosphorus-management capability	1	In states with limits, moving from 0.5% P to 0% P results in reductions of 0.15 g P/person/day (about 6% of influent P)
Cost	5	Currently no significant price difference.
Robustness of system	5	Applies to any flow volume.
Phosphorus-recycling capability	5	This P never enters the system and thus does not need to be recycled.
Maintenance requirements	5	No maintenance requirements
Familiarity to the user	4	May require user to choose appropriate detergent in states where bans have not been enacted.
Weighted Score	4.9	

Table 2-3
Evaluation of Phosphorus-Free Dishwasher Detergents

Criterion	Score	Comment
Proven track record	5	P-free dishwasher detergents have been used for years.
Phosphorus-management capability	2	Reduction from 8.5% P by weight to 0.5% removes avg. of 0.61 g P/person/day (approximately 20% of average influent P) from waste stream for households with dishwashers.
Cost	4	Currently, P-free detergents cost more than those containing P. Removing P from detergents could increase consumer cost approximately $0.70 per box.
Robustness of system	5	Applies to any flow volume.
Phosphorus-recycling capability	5	Removing P from dishwashing detergent means that this P never enters the system and does not need to be recycled.
Maintenance requirements	5	No maintenance requirements.
Familiarity to the user	4	May require user to choose appropriate detergent.
Weighted Score	4.9	

2.2 Source Diversion

Separate treatment of different streams of domestic wastewater makes it possible to isolate those streams where phosphorus is the most concentrated. The primary division of domestic wastewater streams is into blackwater and graywater, where blackwater is from the toilet and graywater is from everything else. Where urine-diverting toilets with separate flushes for the urine and fecal component are used, the blackwater is further classified into “yellowwater” (the urine component) and “brownwater” (the fecal component).

Where low-phosphate or phosphate-free laundry and dishwasher detergents are used, the toilet comprises the greatest source of phosphorus in the house. Microflush toilets, using less than a half gallon per flush (some using less than a cup of water), can help keep the blackwater concentrated enough so that a holding tank becomes a much more economical option than if it is used for all wastewater. Composting the feces and urine on site is another way to segregate the phosphorus from the toilet.

Of the phosphorus in the toilet, two-thirds comes from the urine (see discussion below). Toilets that keep urine from mixing with feces can be plumbed with the urine alone going to a holding tank. When small amounts of water per flush are used, using a holding tank for urine is also a more economical option than using a holding tank for all wastewater.

Segregated blackwater or yellowwater may be treated as septage or, after suitable sanitizing, they may be recycled as a nitrogen-phosphorus-potassium fertilizer in agriculture.

In Norway and Sweden, the industrialized countries that have led recent research on keeping domestic wastewater streams segregated, the desire to recycle nutrients to agriculture has been a prime motivating factor for using source diversion (Skjelhaugen 1999; Höglund 2001; Vinnerås 2002). Swedish practice in recycling urine is discussed in Section 2.2.2.2. The blackwater has been treated through liquid composting, where facilities are available, with the end product used as a soil amendment (see, for example, Skjelhaugen 1999; Norin *et al.* 2000). Liquid composting is an aerobic process that can be managed to attain 60 °C for 24 hours, which effectively pasteurizes the liquid. Scientists like Odd Jarle Skjelhaugen (now director of research at the Agricultural University of Norway) involved in the development of liquid composting believe that the composted blackwater ought to be subject to the same management regulations as animal manure; they are currently regulated as septage (personal communication). Only limited use of liquid composting facilities has been found in the US (for example, Patterson and Short 1985; Deeny *et al.* 1991).

2.2.1 History of Source Diversion

King (1911) noted that forty centuries of agriculture in China had been supported by aggressive reuse of the nutrients in feces and urine as fertilizer. Matsui (1997, cited in Höglund 2001 p. 596) records an old Japanese practice of keeping the urine separate from feces, because the urine made a valuable fertilizer. Höglund (2001) also mentions nineteenth-century German claims of the agricultural value of keeping urine and feces separate, as well as a toilet from the same period that made separate treatment possible by diverting the urine.

2.2.2 Potential for Phosphorus Reduction

The Swedish EPA performed a literature review to arrive at average values for flows and contents of urine, feces, and graywater for Sweden in the mid-1990s (Swedish EPA 1995). Vinnerås *et al.* (Submitted) offered recommendations for revising some of the figures, based on field studies. The 1995 and the revised figures are presented in Table 2-4.

In its literature compilation of contributions from garbage disposals, all other graywater, and toilets, the US EPA found a lower percentage of phosphorus from the toilet: 59% of the phosphorus in domestic wastewater (US EPA 2002; citing phosphorus data from Sedlak 1991), as compared with 74% for Vinnerås and 83% for the earlier Swedish EPA study. The amounts of phosphorus per person from blackwater are, however, similar: 548 grams of phosphorus per year (g P/yr) in the two Swedish studies versus 584 g P/yr in Sedlak (1991). Greater use of phosphate-containing detergents in the US may explain why the amount of phosphorus from the toilet is higher while the percentage is lower.

Crites and Tchobanoglous (1998) give a “typical” figure of 3.2 grams of phosphorus per person, per day (g P/person/day) or 1200g P/person/year from mixed wastewater in households without a garbage grinder. However, the sources used are unidentified and probably include older literature, when phosphate in detergents was higher.

Table 2-4
Composition and Volume of Domestic Wastewater, Annual per Capita Amounts

Unit		Urine		Feces		Toilet Paper		Blackwater		Graywater	
		SEPA	BV	SEPA	BV	SEPA	BV	SEPA	BV	SEPA	BV
Wet mass	kg	365	550	36.5	51	8.9		610		55,000	36,500
Dry mass	kg	21		12.8	11	8.5		40.5		29.2	20
BOD_7	g	-	-	-	-	-	-	-	-	10,200	9,500
COD	g	-	-	-	-	-	-	-	-	26,280	19,000
N	g	4,000		550		-	-	4,550		365	500
P	g	365		183		-	-	548		110	190
K	g	910	1,000	365		-	-	1,365		180	365

The figures are from a literature review by the Swedish EPA (SEPA) (1995) with some proposal for revisions by Vinnerås *et al.* (BV) (Submitted) based on field studies. Where only one number is given, the value in both sources is identical.

Other values found for the mass flows and concentrations of phosphorus in blackwater and graywater are given in the evaluation form for “Blackwater Diversion” in Appendix A.

For the purposes of this discussion, the Swedish values as revised by Vinnerås *et al.* (Submitted) will be used. They are in substantial agreement with what the US EPA uses for the total amount of phosphorus in blackwater, and no US figures were found for fraction of blackwater phosphorus in urine versus feces. While the US EPA reports higher values for phosphorus in graywater, that study is ten years older and phosphate use may well have continued to decrease in the US during that time.

Some composting toilets produce small amounts of effluent in use, if all of the urine is not evaporated. No analyses of the nutrient content of this effluent have been found. For the purposes of comparison, the effluent is considered either to contain negligible amounts of phosphorus or to be collected for treatment off site. If neither of these conditions holds for a given installation, composting toilets may not be as effective in phosphorus management as microflush toilets.

2.2.2.1 Blackwater Diversion

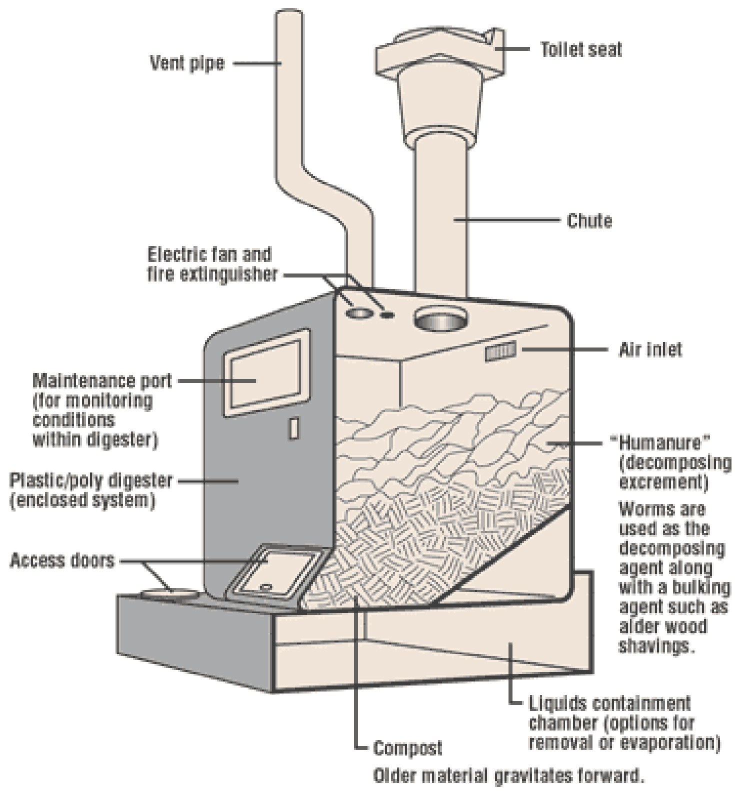
If all phosphorus from the toilet is diverted from the wastewater, the amount of phosphorus in domestic wastewater is reduced by nearly 75%, leaving about 5 mg/L in the graywater.

Composting Toilets

The term "composting toilet" encompasses a wide range of technologies. The common feature for composting toilets is that the feces are collected and retained for a time in the toilet system—either in a chamber of the toilet itself or in a separate chamber—generally in a room below the toilet. The feces may be composted in the toilet system itself or merely collected and retained there for days, with composting or other treatment elsewhere. Composting toilets differ from pit privies, or outhouses, in that composting toilets are designed for a partially or completely composted product to be periodically removed from the system.

The collection system is usually gravity and no water, though microflush toilets (less than 0.1 to 0.5 gal/flush), using either water or foam, may also be attached to composting chambers. Urine may be collected separately, in urine-diverting composting toilets. If urine is not diverted, it may be evaporated during the composting process, or (along with flush water, if any) it may be channeled out of the composting chamber for treatment elsewhere. No studies have been found on the fate of phosphorus in composting toilets such as, what percentage remains in the compost versus what flows out with any excess leachate. If significant amounts of phosphorus are contained in the leachate, then treatment of the leachate for phosphorus may be desirable.

Composting toilets come both in models with the collection chamber in a room below the toilet and ones that are self-contained. For example, the Clivus Multrum (Figure 2-1) has a composting chamber that can be located one or several stories below the toilet.



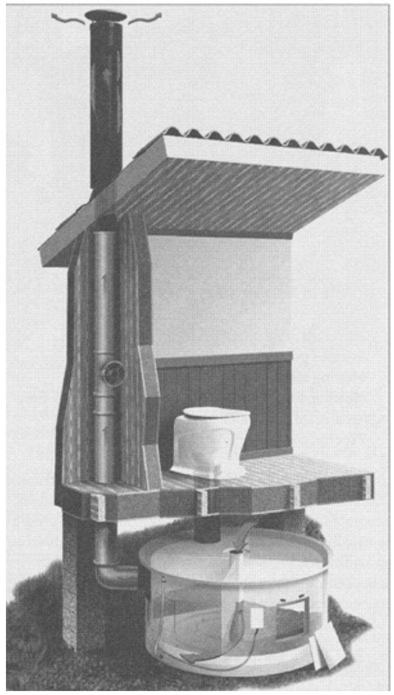
Source: Clivus Multrum.

Figure 2-1
A Schematic of a Clivus Multrum Composting Toilet System

The composting chamber has a sloping floor, and the floor is initially covered with a starter bed of "bulking material," for example, woodchips or sawdust. Solid matter begins its journey at the top of the sloping floor. Glacier-like flowing slowly conveys the mass to the bottom of the unit, where finished compost is removed from an access hatch. Air is drawn from the bathroom through the composting chamber with an electrical fan and is discharged through a vent in the roof.

EcoTech's Carousel (Figure 2-2) has four composting chambers contained in a drum rotating inside a larger chamber, which is placed in a room below the toilet. When one chamber is full, the drum is rotated and the next chamber is filled. When all chambers are filled, the finished compost is removed from the first chamber, and it is rotated in place for filling again.

An example of a self-contained model is Sun-Mar's Excel (Figure 2-3). Composting occurs in the chamber underneath the toilet seat. The toilet seat is elevated (29.5 in., as opposed to about 16 in. for most toilets) to make room for the composting chamber. The composting chamber has three compartments: the "Bio-drum," where composting begins and excess moisture is removed; the finishing drawer, where material from the Bio-drum continues composting; and the liquid evaporation chamber. The Bio-drum is rotated every three to four days and periodically emptied into the finishing drawer. The finishing drawer pulls out of the front of the toilet for emptying.



Source: (Del Porto and Steinfeld 2000)

Figure 2-2
EcoTech's Carousel

Source: http://www.sun-mar.com/2002/SelfcontainedUnits.htm

Figure 2-3
Sun-Mar's Self-Contained Composting Toilet, the Excel

Composting toilets require changes in user behavior to be managed well and therefore to perform well. All three models require addition of bulking material with each use. In addition, periodic maintenance is required, as described above. At least one manufacturer offers maintenance contracts, mostly to public installations, but they also have maintenance arrangements with residential customers, usually with visits twice yearly. Diligent addition of the bulking material after each use, and perhaps other measures (Del Porto and Steinfeld 2000), is required to prevent or eliminate the spread of flying insects into the house.

While the literature reviewing the risks of disease contamination from systems for "dry" handling of feces is extensive, a review of the literature (Cross and Strauss 1986) found little conclusive epidemiological evidence of *actual* transmission to workers or those who consumed the crops, except for nematodes and trematodes. Nonetheless, long-standing cultural beliefs about feces can steer openness to using composting toilets (Cross and Strauss 1986).

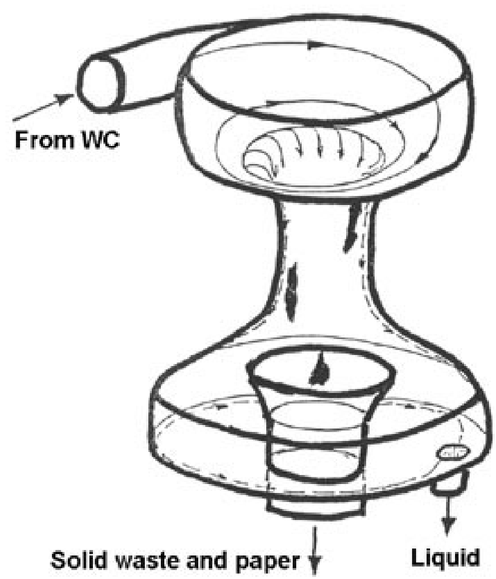
Del Porto and Steinfeld (2000) recommend contacting local and state health authorities for information on legal methods for handling the end product of a composting toilet. They give the example of Massachusetts, where the compost may be buried on site under six inches of soil or removed to a treatment plant by a licensed septage hauler. The compost may be claimed as fertilizer, they report, if it is tested for bacteria, viruses, and heavy metals according to Part 503 of Section 450 of the Clean Water Act.

Table 2-5
Evaluation of Composting Toilets

Criterion	Score	Comment
Proven track record	5	Have been used in a variety of situations since the 1960s, with tens of thousands of units sold since the 1970s.
Phosphorus-management capability	4	Removing blackwater from domestic wastewater reduces phosphorus by 75%.
Cost	3–4	Installed cost $1,600–$6,400; total estimated life-cycle cost $3,600–$7,600.
Robustness of system	3–4	Large load variations have little effect on performance, but lack of maintenance can lead to problems with flying insects and, in some models, difficulty removing poorly composted material. Liquids can impair overall operation if the design does not remove them automatically, for example, through a drain line.
Phosphorus-recycling capability	5	No data found. However, no sorbent is used, so the phosphorus is likely to be as available as in composted manure and nothing potentially hazardous is added (such as heavy metals).
Maintenance requirements	1–2	Maintenance is simple but frequent: Bulking material must be added diligently with every use. The compost is emptied monthly or every couple of years, depending on the model and use.
Familiarity to the user	2	Composting toilets require changes in user behavior to work well, and users may associate them with substandard sanitation.
Weighted Score	3.9 – 4.4	

Separation of Feces From Flush Water (Aquatron)

The Aquatron separates feces and toilet paper from toilet flush water, so they can be composted. It can be used on the flush water from either urine-diverting toilets or toilets where urine and feces are mixed. The separator is a plastic unit shaped like an hourglass (Figure 2-4). The incoming water spirals around the sides of the hourglass. As the water passes through the narrow middle of the "hourglass," solid matter (feces and toilet paper) falls straight down, into an opening of the composting chamber (Figure 2-5). The water continues adhering to the side of the hourglass and exits the bottom. No moving parts are used; the momentum of the flushed water imparts all the spiraling. After exiting the separator, the water is combined with graywater for treatment in a septic tank and soil absorption system. The manufacturer also sells an ultraviolet-disinfection unit for use on the blackwater after the separator; the purpose of disinfecting blackwater that is combined with graywater after disinfection is not clearly described in the literature.

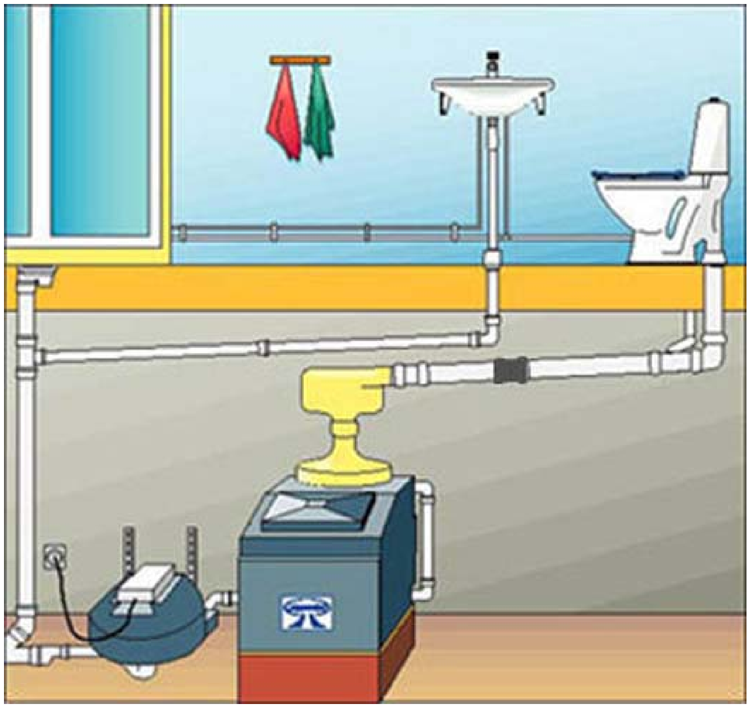


Source: http://www.aquatron.se/graphics/separator.uk.jpg

Blackwater flows in, and solids drop out through the center while liquids whirl around the periphery and exit through the pipe on the bottom.

Figure 2-4
The Aquatron Separator

The Aquatron is designed for toilets of three to six liters (L) flush volume; new US toilets have a maximum of six L flush volume. The maximum distance between the toilet and the separator ranges from 10 to 20 meters, depending on the flush volume. The solids separated by the Aquatron are stored in a "Bio Chamber," where they are composted. Worms may be added to facilitate the composting. Composting reduces the volume by 95%, according to the manufacturer.



Source: http://www.aquatron.se/graphics/frntpage.jpg.

After the separator the blackwater passes through an ultraviolet sanitizing unit and joins the graywater.

Figure 2-5
An Example of a Plumbing System for the Aquatron

Units of various sizes are manufactured. While some are manufactured for commercial facilities and apartment buildings, all are designed to handle the toilet water within a fairly short distance of the toilet, usually inside the same building as the toilet. For that reason, if the technology is to be used with cluster systems, each building connected to the cluster system would have its own Aquatron, and larger commercial buildings may use more than one.

When a short pipe (three meters total length) is used between the toilet and the Aquatron separator, about 70% (error bars bracket 50 to 90%) of fecal nutrients are captured (Vinnerås 2002). With 25% of phosphorus found in the fecal fraction of mixed toilet effluent, the total reduction percentage is about 18% from mixed toilet effluent. If toilet effluent contains 74% of the phosphorus in domestic wastewater, then the total reduction potential using Aquatron is 13%.

Vinnerås (2002) notes from his lab experiments that "an increased loss of nutrients will also occur if water is drained from the separated solids." In actual installations, the Aquatron is designed to let the separated solids be further dewatered by draining. The 13% phosphorus reduction potential is, therefore, probably higher than phosphorus reduction in actual use.

Table 2-6
Evaluation of Aquatron

Criterion	Score	Comment
Proven track record	3	Thousands sold worldwide. Little data found on effectiveness of P removal or technical reliability.
Phosphorus-management capability	1	Maximum potential is 13%.
Cost	3–4	Installed cost $1,600; estimated life-cycle cost $1,600, assuming the user empties the compost. Alternatively, a maintenance contract for annual compost emptying is assumed to cost $300/year, and the life-cycle cost is $8,400.
Robustness of system	4	No information found on the effect of variations in wastewater flows. Given that Aquatron works in the seconds immediately after flushing, performance is expected to be affected by variations in flows only if two toilets connected to the same separator are flushed within seconds of each other.
Phosphorus-recycling capability	5	No data found. However, no sorbent is used, so the phosphorus is likely to be as available as in composted manure and nothing potentially hazardous is added (such as heavy metals).
Maintenance requirements	3	Solids removed every year or two for year-round, single-family homes.
Familiarity to the user	3–5	No change in user behavior from standard septic system if there is a maintenance contract for compost emptying. Otherwise, less frequent maintenance than a dry composting toilet, but the compost still needs to be emptied.
Weighted Score	4.3–4.5	Range: 4.3 (when Cost 4 and Familiarity 3) to 4.5 (when Cost 3 and Familiarity 5)

Microflush Toilets

Microflush toilets use small amounts of water to transport the feces, urine, and toilet paper. They can be connected to the rest of the building's wastewater system, if their primary purpose is to reduce water use. When they are used to manage phosphorus, they are connected to a holding tank. Because of the toilets' minute water use, often less than 1.5 gallons per person, per day (gal/person/day), the holding tank requires emptying much less frequently than when all domestic water is connected to it.

Mix-and-match options with microflush toilets abound. Microflush toilets are available in models that mix the urine and the feces, as well as in urine-diverting models. Microflush toilets can also be connected to a composting toilet system's chamber; either the solids drop into the chamber through an Aquatron, or the excess liquid is removed from the composting chamber with a floor drain and taken to further treatment.

The microflush toilets described here are all vacuum toilets, which use air to transport feces, urine, and toilet paper in the same way as toilets commonly used on airplanes, cruise ships, and trains. Other transport mechanisms in microflush toilets include water with gravity and foam with gravity; vacuum toilets appear to have the best combination of low water use and technical reliability. Use of vacuum to transport the waste greatly reduces the need for water, and it also makes strictly horizontal or even uphill pipe runs possible. Air is the primary transport mechanism for the feces, urine, and toilet paper, with water used primarily to clean the bowl and the pipes. Vacuum is created in the pipes by a vacuum generator, which can be near the toilet or far enough away that its sound is not heard. A single vacuum generator can serve multiple toilets.

Some systems keep a continuous vacuum in the pipe, and instead of a conventional plumbing trap, a mechanical trap is used. When the toilet is flushed, an electronic valve is opened in the trap, and the contents of the toilet bowl are transported by the vacuum in the pipe to the vacuum generator, which then pushes them with pressure to the holding tank (Figure 2-6). Other systems generate vacuum on demand, that is, only when a toilet is flushed. This helps reduce the electricity use of the vacuum generator, since it does not cycle on to maintain a vacuum in the pipe that has been lost to slow leaks.

Source: http://www.folkeweb.no/cgi-bin/webadm.cgi?gid=1022&c=1058.

Figure 2-6
A Vacuum Toilet With the Vacuum Generator Behind the Toilet and the Holding Tank Outside the House

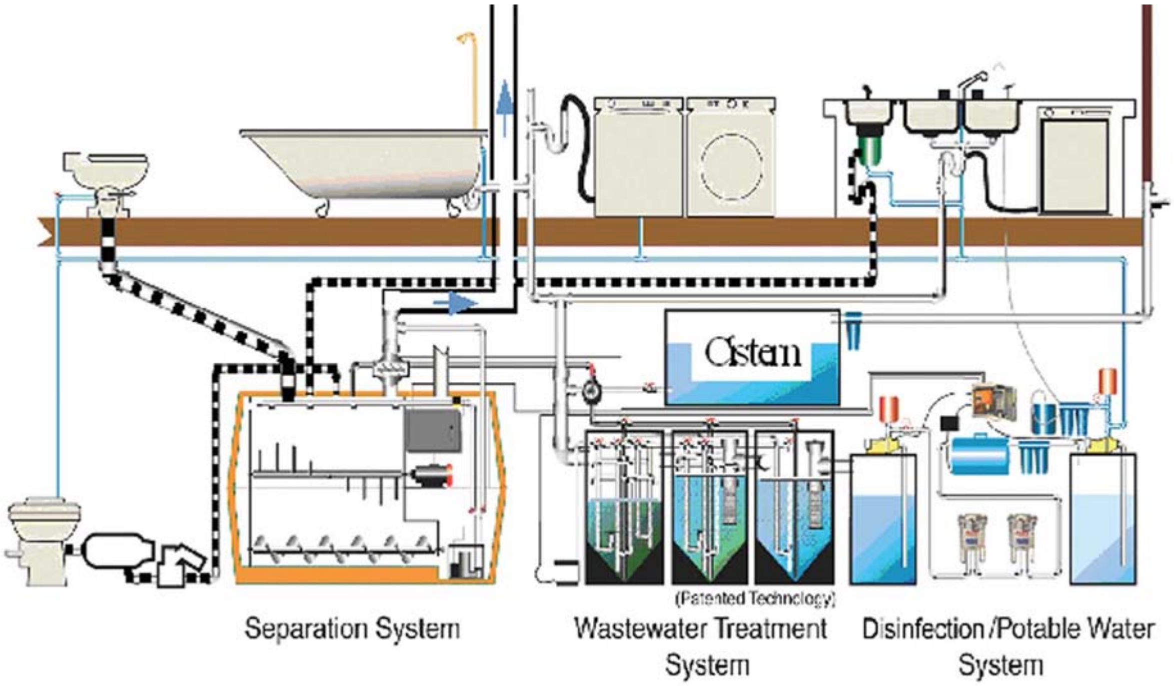
The smallest amount of flush water found was in a toilet with a button for a 0.5 L (17 oz.) flush (for feces) and a button for a 0.25 L (8 oz.) flush (for urine). Another popular vacuum toilet can nominally be set as low as 16 oz. per flush, but the manufacturer says that 24 oz. is a more realistic figure. With these volumes, the toilet could be flushed 3,800 to 6,700 times before a 1,000-gallon holding tank was 90% filled, a target that might be chosen for an alarm to signal that it is time to schedule a tank pumpout.[1]

In the US, marinas collect both straight, concentrated blackwater and mixed sewage from boat tanks. Sean Gowland of The Moorings marina in Colchester, Vermont says their pumpout liquid is taken to a sewage treatment plant, like septage, and treated there. In the absence of laws specifying handling of terrestrial blackwater, the effluent from microflush toilets would most likely be regulated in the same way.

Zero-Discharge Systems

The Infinity Water Recycling System by the Equaris Corporation is essentially a zero-discharge system. The Infinity Water Recycling System is a complete water recycling system that uses a separation tank, an extended aeration treatment system, and disinfection tank to convert 95% of residential waste to carbon dioxide and potable water, according to the manufacturer (Figure 2-7). The remaining 5% biomass contains approximately 19,000 mg P per kilogram and can be used as fertilizer. This system may be appropriate in areas with low water availability. A microflush water toilet is plumbed to a composting chamber. The composting chamber also receives kitchen waste and sludge from the graywater treatment system. The graywater is treated using a combination of settling, extended aeration, filtration, reverse osmosis, and ultraviolet light, and recycled within the house. Six prototypes have been installed.

[1] The calculation assumes 8 toilet visits per day, and that the amount of feces and urine correspond to the "BV" figures in Table 2-4.



Source: Equaris Corporation.

Figure 2-7
Infinity Water Recycling System

Table 2-7
Evaluation of Microflush Toilets

Criterion	Score	Comment
Proven track record	5	A proven track record since the 1970s, with tens of thousands sold per year. (Most are sold for marine applications.)
Phosphorus-management capability	4	Removing blackwater from domestic wastewater reduces phosphorus by 75%.
Cost	1	Installed cost $3,900–$5,800; estimated life-cycle cost $35,000–$44,000.
Robustness of system	5	Not sensitive to variations in wastewater flow or composition.
Phosphorus-recycling capability	5	No data found. However, no sorbent is used, so the phosphorus is likely to be as available as in composted manure and nothing potentially hazardous is added (such as heavy metals).

Table 2-7
Evaluation of Microflush Toilets (Cont.)

Criterion	Score	Comment
Maintenance requirements	3	Replace rubber valves every 5 years at most. A 1,000-gallon holding tank is emptied 1.7 to 3.1 times per year, for a family of who each visit the toilet 8 times per day.
Familiarity to the user	3	The flushing procedure is slightly different, but easy to learn. Some models have a mechanical trap, which must be treated with care when cleaning the toilet. Manufacturers recommend that toilet paper low in adhesives be used, to avoid clogging. The microflush toilets make a different sound than conventional toilets, and the vacuum generator makes a noise, as well.
Weighted Score	4.8	

Table 2-8
Evaluation of Equaris Infinity Water Recycling System

Criterion	Score	Comment
Proven track record	2	Six prototype systems in operation. No monitoring of dissolved P in recirculated water.
Phosphorus-management capability	5	Zero discharge.
Cost	1	$40,000 for the installed system alone.
Robustness of system	4	No specific information, but the closed loop seems to minimize chances of P discharge.
Phosphorus-recycling capability	5	Solid compost generated (approximately 19,000 mg P/dry kg) at 5–15 gallons per 4-person family per year.
Maintenance requirements	1	Significant maintenance/monitoring expected ($400–$500 per year). Unknown how often major components will need replacement.
Familiarity to the user	1	Knowledge of system required by user. User may resist total recycling concept.
Weighted Score	3.1	

2.2.2.2 Urine Diversion

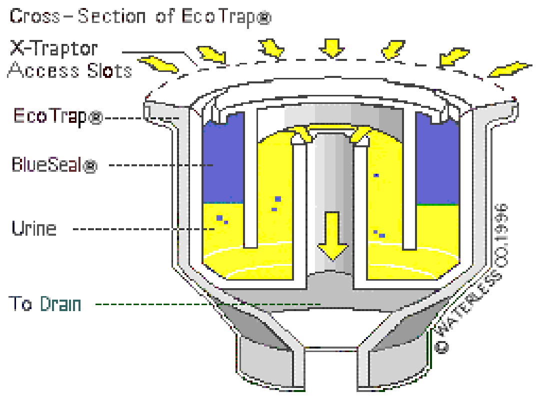
Urine-diverting toilets have separate bowls for urine and feces, with a porcelain wall between them (Figure 2-8). When the user sits on the toilet, urine and feces come out in the direction to fall into the proper bowl. Men can stand or sit when urinating; sitting is more effective in sorting the urine. The urine is flushed with 0.1 to 0.5 L water per use, and flows to a collection tank, which can be a small septic tank. No ventilation of the urine pipe system is needed.

Source: (Johansson 2000).

BB Innovation's Dubbletten toilet (left) and the Wost Man Ecology DS toilet, both constructed from porcelain.

Figure 2-8
Urine-Diverting Toilets

Urinals are another way of diverting urine, and they work quite effectively without requiring men to sit while urinating. The waterless urinal can divert urine for storage at a concentration that is similar to when it leaves the body. For example, the No-Flush™ urinal uses no flush valve, relying on a specially-designed trap (Figure 2-9) to enable the urine to pass out of the urinal while blocking sewer gases from entering the house. The trap is filled with three ounces of BlueSeal® liquid, which is immiscible with water and lighter than water. The liquid must be replenished after 1,500 uses, according to the manufacturer. Flush water is not used; a small amount of water is likely to flow into the collection tank whenever the urinal is cleaned.



Source: http://www.waterless.com/images/urinal1.gif

Figure 2-9
The EcoTrap® Used in the No-Flush™ Urinal

The urine is periodically removed from the collection tank and can be used as fertilizer in agriculture, using the same equipment as for liquid manure. If the urine is to be used in agriculture, storage by itself kills pathogens. Storage can be achieved with two tanks, alternating the collection and storage functions between them, or by storing the urine at the farm where it is to be used, for example, in rubber bladders.

Sweden has been the center of research on the use of urine-diverting toilets, starting in the early 1990s. A researcher there reported that about 3,000 of the most popular models had been sold as of 2000 (Johansson 2000). Researchers from a number of Swedish universities and other research institutions have published many papers, reports, and a number of dissertations on the toilets and their uses. Information for this report is drawn primarily from a review of that literature by the Swedish EPA (2002) and a three-year study by Stockholm Water (Hellström *et al.* 2003).

For numerous reasons, diverting and recycling urine has been viewed as an excellent way to recycle wastewater nutrients. Heavy metal content in urine is very low. For all metals in sewage sludge regulated by the US EPA and for which figures on the levels in urine were found, the urine is below EQ (Exceptional Quality) sludge limits by a factor of more than 10 (Vinnerås *et al.* Submitted; Harrison *et al.* 1999). Arsenic and molybdenum are two metals regulated by the US EPA for sewage sludge applied to land for which no figures were found on the levels in urine. The urine contains more nutrients than any other domestic wastewater stream: about 80% of the nitrogen and about 50% of the phosphorus in the wastewater stream of a typical household is in the urine stream. Finally, the urine requires no special treatment other than storage to kill off all pathogens in it. Researchers at the Swedish Institute for Infectious Disease Control concluded that 6 months of storage at 4 °C is sufficient to kill all pathogens, with the possible exception of viruses, and that 6 months of storage at 20 °C kills all pathogens (Höglund 2001).

In Sweden, the infrastructure for collection of urine varies. It has worked well in Tanum municipality, where local entrepreneurs (mostly farmers who use urine on their fields) collect the urine, providing a service of regular pumpouts much like many septage haulers provide. The municipality agrees to be the collector of last resort, if a system owner is unable to find any commercial service. The farmers store the human urine together with their cattle urine until it is applied, explains Öivind Renhammar, a former politician who pioneered a push to require urine-sorting toilets (personal communication). In other places, where the municipality has taken no responsibility for the urine, the system has broken down, according to Swedish researcher Mats Johansson (Minnesanteckningar 2002).

Stockholm Water has experimented with using urine as a fertilizer in small-grain agriculture. When the urine is applied at nitrogen levels (tons/acre) appropriate for the crops, the phosphorus and potassium levels are also appropriate. They found that harvests of grain fertilized with urine have been 80 to 90% of those fertilized with a roughly equivalent amount of mineral nitrogen fertilizer (Johansson 2000). If ammonia volatilization during urine application is accounted for, the yield of urine-fertilized grain is 85 to 95% of grain fertilized with mineral nitrogen (Johansson 2000).

In practice, depending on how motivated the user is, 65 to 85% of the urine is successfully diverted with these toilets (Jönsson *et al.* 2000, cited in Swedish EPA 2002). From the total wastewater stream, then, 33 to 43% of the phosphorus is removed.

The toilets are of a different design than most plumbers and users are used to. Surveys have been conducted of people who have had the toilet in their homes for six months to three years (Johansson 2000). Some early problems from incorrect installation were discovered and corrected, and experience was gained in quickly fixing clogged urine traps, after which users' attitudes improved (Johansson 2000; Swedish EPA 2002). One model was said to be more difficult to keep clean than a conventional toilet, while another model was said to be easier to keep clean than a conventional toilet. Some male users had stopped using the front bowl when they stood and urinated. The users' attitudes toward these toilets have been most positive where they have been informed of the environmental benefits of the toilets and given instructions in preventing and fixing any stoppages that occur in the urine pipe.

More information on user satisfaction is provided from a Danish survey of 81 allotment gardens where users had used various models of urine-diverting, composting toilets (Backlund *et al.* 2003). Unlike the Swedish surveys, the users in Denmark had all volunteered to try out the toilets. People at only two of the allotment gardens reported that the toilets had not satisfactorily sorted the urine and feces. In both cases, most of the urine from the women went into the feces bowl. However, no problems with odor or maintenance of the toilet were reported for one of these facilities, and a small odor problem was reported at the second, where, nonetheless, their overall impression was that the toilet worked excellently. In addition, another 11 users of the toilets reported that the sorting worked imperfectly either for regular female users or female guests. Of the children whose use was reported, 5 of 24 had some difficulties or had problems with using the toilets. In general, users did not think that any difficulties they had with using the toilets were significant.

Table 2-9
Evaluation of Urine Diversion

Criterion	Score	Comment
Proven track record	5	Thousands of toilets have been sold, and they have been subjects of much research on their function and user acceptance.
Phosphorus-management capability	3	Depending on the motivation of the user and, therefore, the toilet's efficiency in sorting urine, 33 to 43% of the P in domestic wastewater can be removed.
Cost	2–3	Installed cost (including shipping from Europe and cost of an extra 1,000-gallon tank) $4,000; estimated life-cycle cost $9,200–$12,000.
Robustness of system	4	The amount removed is not affected by variations in flows. Reduction would be expected to vary as the percentage of phosphorus in the urine component and the percentage of urine in the wastewater streams vary, perhaps different at schools and restaurants than in homes.
Phosphorus-recycling capability	5	Urine is documented as a useful fertilizer, and heavy metals tested for are at less than 10% of US EPA levels for Exceptional Quality sludge.
Maintenance requirements	3	Yellowwater pumpout intervals vary with sizing; pumpouts every 12 to 18 months are reasonable for single-family houses. Occasional clogging of the urine pipe can usually be fixed with a plumber's snake; caustic soda sometimes is necessary.
Familiarity to the user	2	The toilets work best when user education campaigns are conducted, and when the user self-selects. A high degree of acceptance has been recorded for the toilets, but educating the dwellers and their guests is crucial for the acceptance. Some women and children experience difficulty in sitting so they hit the right bowl with the right substance, and men vary in their willingness to sit while urinating or ability to accurately divert the urine from a standing position.
Weighted Score	4.5 – 4.6	

2.2.3 Evaluation

Table 2-5, 2-6, 2-7, 2-8, and 2-9 indicate how the team has scored the methods evaluated. An explanation of the scoring is in Section 1.5.2.

The most important data source used for blackwater diversion was given a Medium confidence-level rating, using the scale developed as part of this project's QAPP (Etnier *et al.* 2005).

All composting toilets evaluated hold or have held NSF International certification under Standard 41, which is assigned a High confidence level. The conditions the toilets must meet to achieve NSF certification (Etnier *et al.* 2005) ensure that the toilets capture most or all of the phosphorus they receive. Additional important data on composting toilets came from the following sources:

- Manufacturers: Interviews, product literature, websites, product specification sheets, and information provided to the US EPA (Confidence level: Low)
- Abbot, R. 2004. "Skaneateles Lake Watershed Composting Toilet Project." *Small Flows Quarterly* 5(2), 32–39 (Confidence level: High)
- Del Porto, D., and C. Steinfeld. 2000. *The Composting Toilet System Book.* Version 1.2 ed. Center for Ecological Pollution Prevention. Concord, MA. (General information on composting toilets, and some additional information on each evaluated toilet. Confidence level: Low)

The most important data sources used for Aquatron were:

- Manufacturer's website, interviews, and correspondence with manufacturer representatives. (Product size, price, and other data. Confidence level: Low)
- Vinnerås, B. 2002. "Possibilities for Sustainable Nutrient Recycling by Faecal Separation Combined with Urine Diversion." Ph.D., Dept. of Agricultural Engineering, Swedish University of Agricultural Sciences, Uppsala, Sweden. (Data on nutrient removal and product function. Confidence level: Medium)

For the microflush toilet, the most important data source on phosphorus-management potential was the same as for the blackwater diversion method and was assigned a Medium confidence level. Details on specific products' operations were assigned a Low confidence level.

The most important data source for the Equaris Infinity Water Recycling System is assigned a Low confidence level.

For the urine-diverting toilet, all three of the most important data sources were assigned a Medium confidence level.

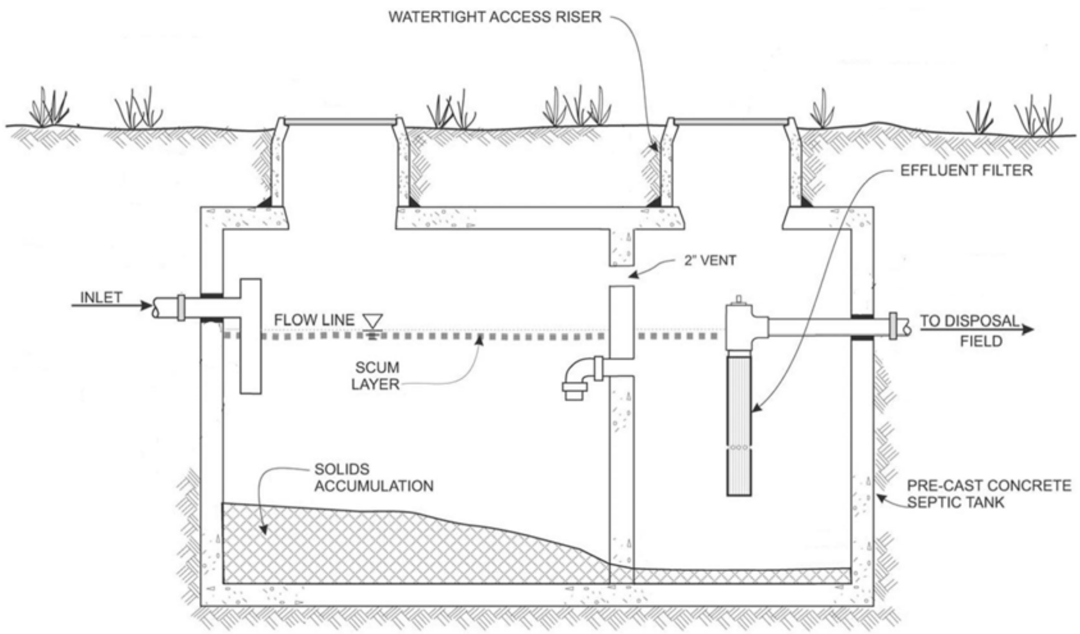
For more details on the QAPP, the data sources, and the assignment of confidence levels, see Etnier *et al.* (2005).

2.3 Septic Tank

2.3.1 History of Phosphorus Management Through Septic Tanks

In the US, approximately 23% of existing homes and one-third of new homes rely on onsite systems for wastewater treatment (US EPA 2002). Septic tanks are the first component of nearly all onsite wastewater systems in the US. The number of septic tanks in use today in the US likely exceeds 26 million.

Septic tanks are enclosed vessels that collect wastewater and separate solids, oils, and grease through settling and flotation. In the tank, settleable solids accumulate as a sludge layer and floatable solids, oils, and grease accumulate in a scum layer that floats on top of the clarified zone (Figure 2-10). The liquid level remains constant: as influent enters the septic tank, an equal amount of effluent is discharged. The greater the volume of the tank relative to daily wastewater flows, the longer the residence time of wastewater in the tank. Longer residence times promote greater wastewater treatment through both settling and digestion (Wilhelm *et al.* 1994). From the clarified zone, septic tanks discharge treated effluent to a soil absorption system or other treatment process.



Source: Questa Engineering Corporation

Figure 2-10
A Septic Tank and Its Parts

Organic wastes in the septic tank are partially digested under anaerobic conditions by microorganisms in the tank, which typically reduce biological oxygen demand (BOD) in the effluent by 30 to 50% (US EPA 2002). Nitrogen and phosphorus compounds are also transformed in the septic tank via microbially mediated processes. Most of the nitrogen and phosphorus that enters the tank in organic molecules from feces, urine, and food waste is converted to mineralized forms: organic nitrogen (urea) to ammonia and organic phosphorus to soluble orthophosphate (Wilhelm *et al.* 1994; Cantor and Knox 1986). Polyphosphates (or condensed phosphates) present in detergents are also hydrolyzed in the tank to orthophosphate (Metcalf and Eddy 1991). Cantor and Knox (1986) report that an average of approximately 85% of phosphorus in septic tank effluent is in the orthophosphate form; Reneau and Pettry (1975) characterize orthophosphate as up to 80% of the total; and data presented in Crites and Tchobanoglous (1998, Table 4-16) indicate that approximately two-thirds of the septic tank effluent phosphorus is orthophosphate. Orthophosphate is the most bioavailable and mobile form of phosphorus; therefore, conversion to orthophosphate in the septic tank has implications for subsequent steps in the wastewater treatment process.

2.3.2 Phosphorus Treatment by Septic Tanks

Septic tanks were not developed to remove phosphorus from wastewater. Cantor and Knox (1986) conclude that septic tanks are not highly efficient in phosphorus removal. The amount of phosphorus removed from the wastewater stream is a function of sludge accumulation in the interval between tank pumpouts. When a septic tank is pumped out, the phosphorus contained in the septage (the sludge, scum, and volume of wastewater in the tank) is removed from the wastewater treatment system.

Due to the assumed low phosphorus-removal efficiency of septic tanks, there are few data available that specifically address this subject. Few sources present both septic tank influent and effluent phosphorus concentrations for the same systems; hence, calculation of removal efficiency is not appropriate. Sources presenting ranges for influent and effluent phosphorus concentrations for septic tanks among multiple systems are not reliable as a means to calculate phosphorus-removal efficiency, given the wide ranges cited and substantial overlap among the ranges for influent and effluent concentrations. For instance, in reviewing treatment performance of onsite systems, Metcalf and Eddy (1991) cite phosphorus concentration ranges of 10 to 27 mg/L for raw wastewater and 10 to 30 mg/L for septic tank effluent. Likewise, Crites and Tchobanoglous (1998) give a typical range of 4 to 15 mg/L total phosphorus in domestic wastewater and 12 to 20 mg/L total phosphorus in septic effluent. It is not reasonable to calculate any removal efficiency from these data, although they appear to support the judgement that little phosphorus removal occurs in the septic tank. (Since the high ends of the ranges are *higher* for septic tank effluent than for raw wastewater, it almost looks like the septic tanks *produce* phosphorus.)

In a summary of Scandinavian and US sources, Refsgaard and Etnier (1998) found 3 to 5% phosphorus sequestration in septic tanks.

A recent estimate of phosphorus-removal efficiency of a conventional septic tank was developed by the Ventura Regional Sanitation District (2001) in a demonstration study of several advanced onsite sewage dispersal systems. A 1,500-gallon, two-chamber septic tank was used as a control in the experiment. Wastewater flows to the tank averaged 401 gallons per day through the test period. The mean influent phosphorus concentration for the duration of the test period was 3.2 mg/L, which is at the low end of the range reported in the literature. The mean effluent phosphorus concentration was 2.9 mg/L, a 9% reduction in total phosphorus. The ranges in phosphorus concentration were 2.3 to 4.5 mg/L and 2.0 to 3.3 mg/L for influent and effluent, respectively. Despite substantial overlap in the ranges, these data suggest marginal phosphorus removal during normal system operation.

Pell and Nyberg (1989) estimated a phosphorus-removal efficiency of 48% in a septic tank, much higher than any other estimate found in the literature. This figure comes from a study only during system start-up; a three-chamber septic tank was followed in the first 78 days of operation. Furthermore, the Pell and Nyberg experiment was conducted using artificial wastewater in a three-chamber tank only 190 L in size; it may be inappropriate to extrapolate test results to conventional septic tanks treating true wastewater. Pell and Nyberg's results are not believed to be indicative of long-term phosphorus-removal efficiencies in septic tanks.

Support for the conclusion that phosphorus-removal efficiency of conventional septic tanks is low is found by comparing standard values for the phosphorus in accumulated septage with influent phosphorus loads. If the phosphorus accumulated in the septage represents the phosphorus removed from the wastewater stream in the interval between pumpouts, average removal efficiency within this interval may be estimated by comparing the phosphorus accumulated in the tank with the phosphorus load in the wastewater. Septage accumulates at rates of approximately 227 liters/person/year (Crites and Tchobanoglous 1998). Using the US EPA's suggested design value for total phosphorus in septage of 250 mg/L (Crites and Tchobanoglous 1998), the accumulated septage from a single person each year (after digestion in the septic tank) would contain 57 g total phosphorus. This amount is equivalent to only 3.4 to 5.8% of the per capita total phosphorus loading rate in domestic wastewater, estimated as 2.7 to 4.5 g/person/day (Crites and Tchobanoglous 1998).

2.3.3 Potential for Further Phosphorus Reduction

Chemical precipitation of phosphorus using aluminum, iron, and calcium compounds may dramatically lower effluent phosphorus concentrations from septic tanks (US EPA 2002). Brandes (1977) describes early research into the use of alum (aluminum sulfide). A commercially available product that uses an aluminum-based precipitant as an addition to a conventional septic tank was investigated in detail. In this method, the precipitant is dispensed at timed intervals into a wastewater pipe in the house. Phosphorus precipitates out in the wastewater pipes and in the septic tank, and both the primary sludge and the chemical sludge are collected in the septic tank. The increased sludge production, however, means the septic tank needs to be pumped out two to three times a year on average. A major factor in the excessive sludge production is the unfavorable stoichiometry of the precipitation reactions. For example, Cantor (1986) estimates that in practice it would take 22.0 g of alum to precipitate 1.0 g of phosphorus. Due to the greatly increased frequency of septic tank pumping entailed and the issues of handling chemical sludge, chemical precipitants were not reviewed further in this study.

The fate of septage removed from onsite systems is not reviewed in depth here. In the US, most septage is land-applied or trucked to a wastewater treatment plant. The primary benefit of land application is that it returns nutrients to agricultural land. Most states have regulations concerning septage management through land application. Treatment of septage at wastewater treatment plants precludes beneficial use of the material and consumes energy, but this is the preferred practice where land application is considered unfeasible or undesirable. Trucking sludge to land application sites or wastewater treatment plants uses energy. Application of septage to agricultural fields may represent an energy savings over production and application of equivalent amounts of commercial fertilizer, if transport distances are short.

2.3.4 Evaluation of the Septic Tank and Alum Injection

Septic tanks were included in this project because they constitute the first component of the wastewater treatment train, and because Gold and Sims (2000) cited the finding by Pell and Nyberg (1989) that "as much as 48%" of wastewater phosphorus is removed in a septic tank. An objective of this project was to find data on the effect of septic tank design and pumpout strategies on phosphorus-removal capability. However, investigation of the literature showed that Pell and Nyberg's figure was an outlier, and represented only the first 78 days of operation of a 190 L septic tank using artificial wastewater. The other data examined consistently showed low removal rates, around 5% or less. No literature was found indicating ways to increase the phosphorus-removal rate in the septic tank (other than 78-day pumpout intervals), and septic tanks are almost universally used in decentralized wastewater treatment. For these reasons, the septic tank as a phosphorus-management method was not subject to formal review using the project's criteria. Table 2-10 shows the evaluation of an alum injection method. An explanation of the scoring is in section 1.5.2.

The most important data source used for alum-injection was given a Medium confidence-level rating, using the scale developed as part of this project's QAPP. For more details on the QAPP, the data sources, and the assignment of confidence levels, see Etnier *et al.* (2005).

Table 2-10
Evaluation of a Technology for Alum Injection

Criterion	Score	Comment
Proven track record	2	Not fully known. Published research on use of alum since at least 1977. Two units were used in single-family houses in an independent, two-year Swedish study that began in early 2000.
Phosphorus-management capability	4	50 to 90%, highly dependent on dose.
Cost	1	Installed cost $2,400; estimated life-cycle cost $34,000 (dominated by cost of frequent pumpouts).
Robustness of system	3	Stable throughout year, but P removal varies with dosage.
Phosphorus-recycling capability	3	According to manufacturer, similar P availability to wastewater treatment plant sludge.
Maintenance requirements	2	Septic tank pumpouts required 2 to 3 times per year.
Familiarity to the user	4	User most likely needs to know how to refill the dosing container. Otherwise, no change in user behavior from a standard septic system.
Weighted Score	3.1	

2.4 Post-Septic Tank Treatment

Post-septic tank (PST) treatment can be accomplished through a wide range of secondary and tertiary treatment options. The majority of PST systems reviewed in this study still require discharge into a soil absorption system, although in some cases the soil absorption system area can be minimized. In general, PST systems designed for nutrient removal have focused on nitrogen removal (Gold and Sims 2000). The enhanced interest in phosphorus discharge from onsite systems, however, has led to both the development of new PST methods specifically designed for phosphorus treatment and the reevaluation of existing PST treatment systems for phosphorus removal.

Phosphorus removal from waste streams can occur via physical, chemical, or biological mechanisms. Microbial uptake of phosphorus for cell synthesis during secondary biological treatment accounts for a 10 to 40% reduction in phosphorus concentration (Crites 1998). Furthermore, microbial uptake is enhanced in sequencing batch reactor (SBR) systems, which alternate anaerobic and aerobic treatment (US EPA 2002; Crites 1998). A number of proprietary SBR processes are commercially available and are often combined with a chemical precipitant dosage step. As a result of the considerable amount of sludge produced with chemical dosing, however, these methods do not score highly in this evaluation.

The primary physical and chemical mechanisms for phosphorus removal in PST systems can be subdivided into sedimentation processes or interactions with specially designed filter media or nanoparticle selective resins. Sedimentation of particulate (organic) phosphorus is largely a function of the hydraulic residence time of the wastewater treatment system, and only accounts for a maximum of 10 to 20% of the total phosphorus in raw sewage (US EPA 2002). Physical and chemical interactions of dissolved (inorganic) phosphorus with filter media and nanoparticle selective resins, however, have become an area of considerable interest. These systems predominantly consist of a combination of iron, aluminum, and/or calcium with a natural or synthetic-based medium. When in contact with a waste stream, dissolved phosphorus can complex or adsorb onto the insoluble metallic surfaces. The operational life of these systems, however, is limited by the availability of reactive sites on the filter media, which require regeneration or replacement when saturated.

This section provides a review of the current PST methods for which phosphorus-removal data are available and recommendations of areas for future research into phosphorus treatment.

2.4.1 Methods

In general, PST treatment systems designed for phosphorus removal fall into four categories:

- Sand and modified sand filters
- Organic material-based filters
- Nanoparticle selective resins
- Aerobic treatment with chemical dosing

A brief review of each of these categories, as well as a description of the most promising methods in each category, is given in the following subsections.

2.4.1.1 Sand and Modified Sand Filters

Various sand and modified sand filter (Figure 2-11) media have been investigated for phosphorus removal. Some of the most promising methods are described in this section.

RUCK CFT Systems, Holmes and McGrath, Inc.

The RUCK CFT treatment system, developed by Rein Laak of the University of Connecticut, is located between the septic tank and soil absorption system and is designed primarily for nitrogen removal in nitrogen-sensitive areas. The RUCK CFT system grows out of the RUCK system (Laak 1988) and is used to treat larger flows, having been used at sites producing as much as 16,500 gal/day of waste. The RUCK CFT system differs slightly from the traditional system in that all waste streams are sent through the RUCK filter and an external carbon source (soap) is added to the system in the mixing chamber (Figure 2-12), while the RUCK system first separates the wastewater stream into blackwater and graywater and recombines them in the mixing chamber. Significant phosphorus removal has been observed in RUCK CFT systems.

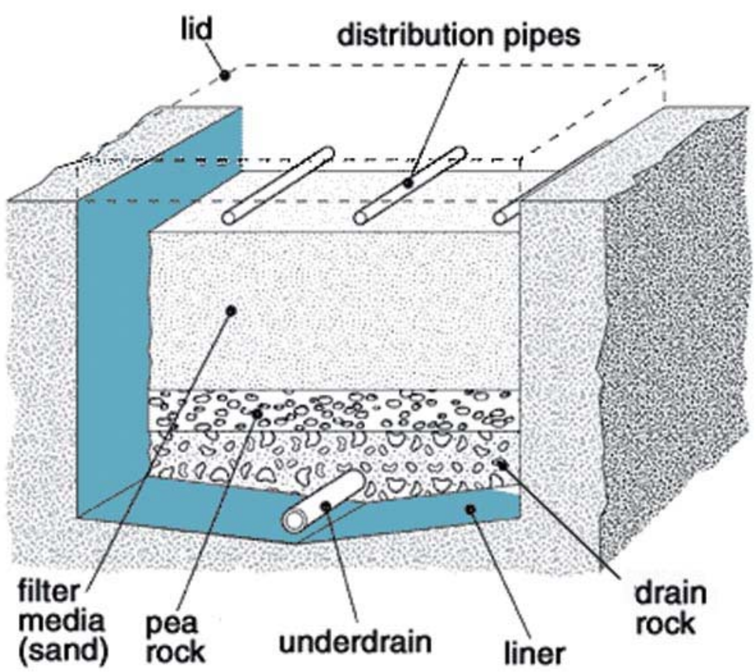


Figure 2-11
Example of a Sand Filter

The major components of the RUCK CFT systems are a septic tank, the RUCK filter, and a mixing chamber/second septic tank, followed by effluent dispersal. The RUCK filter consists of alternating layers of a fine mason sand and double-washed 3/4-in. stone, and is vented in order to maintain aerobic conditions and enhance microbial nitrification. A carbon source (soap) is added in the mixing chamber.

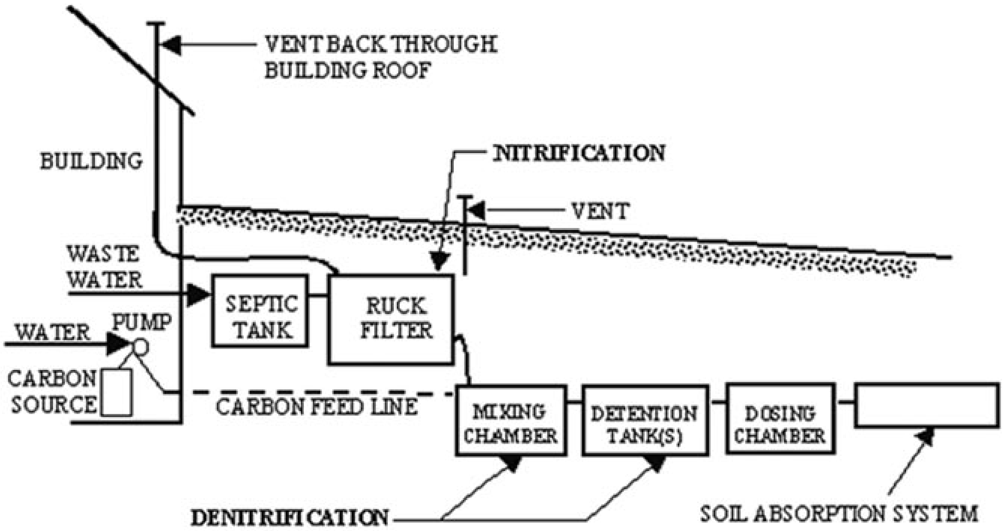


Figure 2-12
Schematic Diagram of a RUCK CFT System

The manufacturers hypothesize that phosphorus removal in the RUCK CFT filter is from sorption and sedimentation in the sand filter. They believe the phosphorus removal process is enhanced by the low pH (less than 5) in the RUCK filter after aerobic nitrification. However, long-time onsite system researcher James Converse reports (personal communication) that tests of 50 sand filters by the University of Wisconsin–Madison found an average pH of 7, so it is not clear how often the low pH requirements will be met. Nitrification releases carbonic acid and consumes alkalinity, but it takes place optimally at pH 6.5 to 8, and in low-alkalinity waters it may be inhibited by the lack of alkalinity (Oakley 2003). Data for phosphorus removal are limited to two RUCK CFT units, which have been operating for two to four years in Massachusetts. Phosphorus-removal rates as high as 90% were observed.

Construction and installation costs for a RUCK CFT system were estimated to be $10,000 more than a conventional septic system. Adding operation and maintenance costs over a 30-year life cycle, including inspections, pump replacements, and filter replacements, brings the 30-year life-cycle cost of this system to $25,000 more than that of a conventional septic system.

Other Enhanced Phosphorus-Removal Methods Using Packed-Bed Filters

Packed-bed filters may be enhanced for phosphorus removal by adding an iron, aluminum, or calcium-containing compound to the waste stream or filter media. For example, Davis (1999) observed an increase in total phosphorus-removal efficiency from 34 to 58% and an increase in orthophosphate removal efficiency from 20 to 85% after the addition of lime (CaO) to a sand filter influent. Other methods have shown a high efficiency for phosphorus removal from metal-containing filter media. Richter and Weaver (2004) have observed an increase in phosphorus-removal efficiency of 17 to 60% in constructed wetlands when filled with shredded steel-belted tires as compared to gravel. Likewise, crushed red bricks (Ayres Associates 1998), as well as lightweight clay aggregates (Ayres Associates 1998; Jenssen *et al.* 2002) have shown phosphorus-removal efficiencies exceeding 90%. Slag from a basic oxygen furnace has been observed to remove greater than 97% of total phosphorus (Lombardo 2003). In each of these methods, phosphorus removal is enhanced through complex formation with the metallic components of the filter media.

A commercially available lightweight clay aggregate and a filter using basic oxygen furnace slag are described in more detail as follows:

Lightweight aggregates are made of expanded clay; they are a sort of clay "popcorn" with high surface area and are often used in horticulture. Filtralite® and Utelite® are two brands that have been used in wastewater treatment. The aggregates can be used as a medium in packed-bed filters of various designs. Jenssen *et al.* (2002) studied the performance of 12 subsurface-flow constructed wetlands that were packed with lightweight aggregates. In this study, the average phosphorus removal from the wetlands ranged from 79 to 98%, with effluent concentrations well below 1 mg/L. Another study found a 94% phosphorus-removal efficiency in a test facility (Ayres Associates 2000). Lightweight aggregate systems described by Jenssen *et al.* (2002) were designed with the capability to remove greater than 90% of phosphorus for 15 years; the oldest system has been in use since 1991.

Construction and installation costs for the lightweight aggregate packed bed used in the Ayres Associates tests (2000) were estimated to be $8,600 more than a conventional septic system. Total costs over a 30-year life cycle, including inspections, pump replacements, and medium replacements, were estimated to be $25,000 more than that of a conventional septic system. Calculations were made on the basis of using an imported aggregate; costs for a domestic aggregate have not been investigated but can be expected to be less.

A commercially available packed-bed filter using basic oxygen furnace (BOF) slag consists of a mixture of fine (less than 25μm) oxides of iron and calcium and other coarse materials (0.5 to 5.0 mm); either sand alone or sand and limestone. The fine particles are derived from the BOF slag and are numerous enough to substantially coat the coarse particles, but no more than 20% of the total weight of the medium, so as to not clog the interstices. The phosphates in the effluent react with the fine metal oxides on the surface of the coarse particles to form calcium and iron phosphates. No sludge is produced; phosphate precipitates on the outside of the medium. Greater than 97% removal of total phosphorus has been observed with this system. The medium is expected to become saturated with phosphorus eventually, so medium replacement needs to be part of long-term maintenance. The effluent from the packed-bed filter has a high pH (10 to 12), so some method of neutralizing the effluent may be required before dispersal. The US vendor recommends a peat filter for neutralization of small to medium flows and suggests other methods, like addition of carbon dioxide, for neutralization of larger flows.

Construction and installation costs for a system using BOF slag were estimated to be $11,000 more than a conventional septic system. Operation and maintenance costs over a 30-year life cycle, including inspections, pump replacements, and sand filter medium replacements, were estimated to bring the 30-year life-cycle cost to $23,000 more than that of a conventional septic system.

PhosRID™ Filter System, Lombardo Associates, Inc.

The PhosRID™ Filter System is located directly between the septic tank and soil absorption system and is designed specifically for phosphorus removal. PhosRID is based on principles described by Robertson (2000), who found that under acid conditions, ferric iron solids release low levels of dissolved ferrous iron, which precipitates phosphorus when oxidized.

Dissolved phosphorus is removed from a waste stream through the formation and precipitation of Fe-P (iron-phosphorus) complexes via a series of two oxidation/reduction steps. In the first step, septic tank effluent is passed through a filter containing an Fe (III)-rich soil medium. The reducing capacity of the organic-rich septic effluent causes the reductive dissolution of iron hydroxides—Fe (II)—into the waste stream. The dissolved iron hydroxides then react with phosphorus-containing molecules in the waste stream to form Fe-P complexes. In the second step, the waste stream, now containing the dissolved Fe-P complexes, is passed through a sand filter. Oxidation of Fe (II) to Fe (III) in the aerobic environment results in the precipitation of both Fe and P from solution and onto the medium of the sand filter. Greater than 90% total phosphorus removal has been observed in the effluent from the PhosRID™ Filter System. In addition, both total nitrogen and BOD reduction can be expected from the PhosRID™ Filter System. Performance of the PhosRID™ system has been evaluated by the Massachusetts Alternative Septic System Test Center (MASSTC) for a total of two years.

The PhosRID™ system is projected to cost approximately $10,000 for an individual property, in addition to the septic tank and soil absorption system. With operation and maintenance costs over a 30-year life cycle, including inspections, pump replacements, and filter medium replacements, the total costs were estimated to be $18,000 to $28,000 more than that of a conventional septic system. (The $10,000 difference in life-cycle cost estimate depends on whether the system is inspected twice yearly or once every five years.)

2.4.1.2 Organic Material-Based Filters

Organic materials, such as sphagnum peat moss and lignocellulose, have been incorporated into phosphorus treatment applications. Sphagnum peat moss, more commonly used as a treatment medium in aerobic treatment, has been shown to adsorb dissolved phosphorus (Brooks *et al.* 1984; Couillard 1994; Nichols and Boelter 1982); however, the sorption capacity of peat mosses will decrease substantially with time, according to Dennis Martin at Simmering & Associates, a company that formerly manufactured Peatland (personal communication). Patterson (2004) observed an average phosphorus removal of 75%; however, the system showed a steady decrease in phosphorus removal over an eleven-month period. Different peat mosses may vary greatly in coarseness and surface area, and thus will exhibit a wide range in sorption capacity for phosphorus (personal communication, Dennis Martin, Simmering & Associates).

Some authors have found a longer-term effectiveness for peat. Nichols and Boelter (1982) report on a facility that was achieving 99% phosphorus removal after eight years, though 45% of that was estimated to be in vegetative uptake and the effluent went through both peat and sand. Both Nichols and Boelter (1982) and Couillard (1994) report on different factors that have been hypothesized to increase phosphorus uptake in peat: presence of aluminum and iron in the peat, and microbial immobilization.

The Peatland Sewage Treatment System, sold by Premier Tech, is an example of a commercially available treatment system that uses a fine peat moss with a relatively high sorption capacity for phosphorus. It also mixes sand in with the peat, and the manufacturer says that the sand particle size affects phosphorus removal—finer particles lead to greater phosphorus removal. Peatland also incorporates a wetland after the peat filter, which further increases phosphorus uptake and probably extends the useful lifetime of the system.

Peatland™ Sewage Treatment System, Premier Tech

The Peatland Sewage Treatment System is a two-component system that combines a sphagnum peat filtration unit with a subsurface constructed wetland. In this system, septic tank effluent first passes through a filtration unit comprised of a mixture of a sphagnum peat moss and granular materials (sand) and then through the high-density root systems of a subsurface-flow constructed wetland. In general, the system is designed to efficiently remove pathogens as well as BOD, TSS, and nitrogen to a level suitable for surface discharge. Phosphorus removal was also observed in the system by sedimentation of particulate phosphorus and adsorption of dissolved phosphorus in both the peat filter and the constructed wetland. At two different locations in Canada, greater than 80% phosphorus removal was demonstrated by the Peatland Treatment System during the initial one to three years of operation. No long-term studies on phosphorus removal are available at this time; however, it is expected that the phosphorus-sorption capacity of the peat filter will decrease much more rapidly than the filter's ability to otherwise treat the septic tank effluent.

In order to be more cost effective, the Peatland Treatment System is marketed as a cluster system component. The price of materials for this system is between $10.50 and $12.50 per gallon of waste treated per day, in addition to the cost of the septic tank and soil absorption system. Construction and installation costs for a Peatland system were estimated to be $10,000 more than a conventional septic system. Operation and maintenance costs over a 30-year life cycle, including inspections, pump replacements, and peat filter replacements, bring the total life-cycle cost to $27,000 more than that of a conventional septic system.

In addition to peat-based filters, lignocellulose fibers have been shown to effectively remove phosphorus from waste streams. The New York City Department of Environmental Protection has overseen the use of iron- and aluminum-containing lignocellulose fibers to remove phosphorus from milking station effluent in the New York City watershed (Han 2002). Initial results from this study suggest a 29 to 42% removal of phosphorus from a milk station waste stream containing 60 to 68 mg/L total phosphorus. More efficient removal of phosphorus by lignocellulose fibers can potentially be expected from residential waste streams, which only contain 4 to 15 mg/L phosphorus (Crites and Tchobanoglous 1998). Further work is needed to quantify the sorption capacity and operational lifespan of lignocellulose fibers.

2.4.1.3 Nanoparticle Selective Resins

Nanoparticle selective resins have been designed and tested in pilot-scale operations for selective removal of phosphorus from waste streams (Zhao and Sengupta 1998; Wang and Sievers 2004; Petruzzelli *et al.* 2003). In the phosphate-selective resin used in these studies, immobilized copper (II) ions on the resin surface selectively bond to dissolved orthophosphate anions. Orthophosphate is then released from the resin surface when a regeneration solution (6% sodium chloride (NaCl); pH 4.3) is passed through the system. Furthermore, the dissolved phosphorus in the regenerate can be recycled as a fertilizer after a chemical precipitation is performed.

In a technology similar to the above, an iron-based nanoparticle selective resin has been sold as an arsenic removal product for a range of applications ranging from under-the-sink filters to municipal wastewater systems. The manufacturer claims the product has a high capacity for arsenic, vanadium, uranium, and phosphate and can be regenerated using a 2% NaCl, 2% sodium hydroxide (NaOH) solution. A system was built in Florida that uses the iron-based resin to remove phosphorus from an agricultural waste stream containing 30 to 40 mg/L total phosphorus. This treatment system consists of two 4-cubic foot treatment chambers filled with the resin, capable of treating 20 gallons per minute each, which are used in conjunction with a chemical flocculation step.

Regeneration of the resin is controlled through an automated system and occurs after 50,000 gallons have been treated or no longer than seven days of operation. The manufacturer recommends that the regenerant be used twice before removal of the phosphorus. To remove the phosphorus, the pH is reduced and the phosphorus precipitated. After precipitation, the regenerant is recharged with NaOH. The same volume of fluid can go through this pH reduction, precipitation, and recharge cycle four times. Therefore, assuming appropriate chemical storage and handling, one volume of regenerant water can treat up to eight columns. The solid residual flocculent is used as an agricultural fertilizer. This system in Florida has been running full-scale since approximately April 2004, and it reduced phosphorus levels in the effluent to below 0.5 mg/L. A full-scale evaluation of the system, however, will not be released by the evaluating party until after one year of operation.

Because the regenerant used is caustic, training and licensing is required for the users, says the manufacturer (personal communication, Ted Shields, Solmetex). This requirement would appear to preclude most use of the technology for individual systems; for cluster systems, the operator would need to be trained and licensed in chemical handling.

Cost analysis by Wang and Sievers (2004) as well as by Zhao and Sengupta (1998) estimate the cost of using one technology to reduce the orthophosphate in solution from 4 mg/L to less than 0.5 mg/L to be between \$0.06 and \$0.30 per 1,000 L (265 gallons) of wastewater treated. At this time, however, that resin has not been used in commercial domestic applications. A system designed for 50,000 gal/day agricultural wastewater costs around \$13,000 to install, according to Brian Roy of Royal Consulting Services, who works with the system.

2.4.1.4 Aerobic Treatment Units With Chemical Dosing

Aerobic treatment units (ATUs) that add a chemical precipitation step can be effective at phosphorus removal. Because of the large volume of sludge they produce, only two products were chosen to indicate the strengths and weaknesses of this method. Both products were recently evaluated in field conditions for phosphorus removal and many other parameters. The extended-aeration activated sludge unit is a continuous flow system that passes septic tank effluent through a three-chambered reactor and chemical dosing chamber. Nitrogen removal occurs in the reactor via microbial denitrification, and phosphorus is subsequently removed during the chemical dosing step. With proper dosing, phosphorus removal of 90 to 99% can be achieved from the system. Sludge removal is typically required twice a year. Construction and installation costs for the system were estimated to be $9,700 more than a conventional septic system. Adding operation and maintenance costs over a 30-year life cycle, including maintenance, inspections, and pump replacements, brings the life-cycle cost of this system to $44,000 more than that of a conventional septic system.

The sequencing batch reactor receives an intermittent flow of effluent from a septic collection tank and treats it in a five-hour automated process. An aluminum-based chemical precipitant is added to the system during the treatment process, and when working properly, can result in an 80% reduction in phosphorus. In addition, the system stores and dries excess sludge in filter bags that can easily be dried and removed for composting. The literature is not explicit on amounts of sludge generated; apparently emptying the sludge sacks is not required more than three times a year, and the quantities are characterized as “small” (Hellström *et al.* 2003; af Petersens 2003). Construction and installation costs for a system were estimated to be $11,000 more than a conventional septic system. Operation and maintenance costs over a 30-year life cycle, including maintenance, inspections, and pump replacements, were estimated to bring the life-cycle cost of this system to $37,000 more than that of a conventional septic system.

2.4.2 Evaluation

The following tables indicate how the team scored the methods evaluated. An explanation of the scoring is in section 1.5.2.

The most important data source used for RUCK CFT was given a Low confidence level rating using the scale developed as part of this project’s QAPP. For more details on the QAPP, the data sources, and the assignment of confidence levels, see Etnier *et al.* 2005.

For lightweight aggregates, the three most important data sources were:

- Maehlum, T. *Cold-Climate Constructed Wetlands: Aerobic Pre-Treatment and Horizontal Subsurface Flow Systems for Domestic Sewage and Landfill Leachate Purification.* Doctoral Thesis. Agricultural University of Norway. 1998. (Confidence level: High)
- Zhu, T. *Phosphorus and Nitrogen Removal in Lightweight Aggregate (LWA) Constructed Wetlands and Intermittent Filter Systems.* Doctoral Thesis. Agricultural University of Norway. 1998. (Confidence level: High)

- *Florida Keys Onsite Wastewater Reduction Systems Demonstration Project.* Ayers Associates. April 2000. (Confidence level: Medium)

For BOF slag and PhosRID, the most important data source is assigned a Medium confidence level.

For the Peatland system, the most important data source is assigned a Low confidence level.

For the aerobic treatment units with chemical dosing, the most important data source is assigned a Medium confidence level.

For more details on the QAPP, the data sources, and the assignment of confidence levels, see Etnier *et al.* (2005).

Table 2-11
Evaluation of RUCK CFT

Criterion	Score	Comment
Proven track record	3	Over 200 RUCK systems in use, the first of which date to 1977. P treatment data, however, only available for two RUCK CFT systems.
Phosphorus-management capability	3	30 to 90%, only two sources of data for P removal available.
Cost	1	Installed cost $10,000; estimated life-cycle cost $25,000.
Robustness of system	4	No specific information, but packed-bed filters are generally little affected by variations in wastewater flow and composition.
Phosphorus-recycling capability	3	No specific information; the system involves a sorbent but it is unlikely to be contaminated by heavy metals.
Maintenance requirements	3	The RUCK filter has never been replaced in any system (over 200 systems dating over 25 years); the RUCK CFT has a shorter track record. Manufacturer claims the system has capacity to sorb P for many years; however, no long-term phosphorus studies are available. Replacement of the RUCK filter is expected to be expensive/difficult. Some standard maintenance required (refilling carbon source tank).
Familiarity to the user	4	User may be required to add carbon source to system.
Weighted Score	3.4	

Table 2-12
Evaluation of PhosRID™

Criterion	Score	Comment
Proven track record	2	Two systems, two years longest. Test results available from MASSTC.
Phosphorus-management capability	5	Greater than 90% phosphorus reduction
Cost	1	Manufacturer estimates $10,000 to install. Estimated life-cycle cost $18,000 to $28,000.
Robustness of system	4	No specific information, but packed-bed filters are generally little affected by variations in wastewater flow and composition.
Phosphorus-recycling capability	4	Sand containing precipitated phosphates can be used in agriculture; no data to confirm availability.
Maintenance requirements	4	No major component needs to be replaced after two years of operation; no long-term studies available. Iron medium needs to be replenished—estimated every five years.
Familiarity to the user	5	No change in user behavior from standard septic system.
Weighted Score	4.0	

Table 2-13
Evaluation of Lightweight Aggregates in Packed-Bed Filters

Criterion	Score	Comment
Proven track record	5	Used in nearly 100 systems, with at least 12 monitored, one since 1991. Many lab experiments, as well.
Phosphorus-management capability	5	70 to 99%. Expected to decrease as the medium becomes saturated with phosphorus.
Cost	1	For a bed like that used in Florida Keys tests, estimated installed cost $8,600; estimated life-cycle cost $25,000.
Robustness of system	4	No specific information, but packed-bed filters are generally little affected by variations in wastewater flow and composition.

Table 2-13
Evaluation of Lightweight Aggregates in Packed-Bed Filters (Cont.)

Criterion	Score	Comment
Phosphorus-recycling capability	4	Spent sorbent has been applied as fertilizer.
Maintenance requirements	4	Assumed to be similar to sand filters.
Familiarity to the user	5	No change in user behavior from a standard septic system.
Weighted Score	4.5	

Table 2-14
Evaluation of Basic Oxygen Furnace (BOF) Slag in Packed-Bed Filters

Criterion	Score	Comment
Proven track record	3	Three systems, five years longest.
Phosphorus-management capability	5	Greater than 97% total P.
Cost	1	No cost figures available from manufacturer. Estimated installed cost $11,000; estimated life-cycle cost $23,000.
Robustness of system	4	No specific information, but packed-bed filters are generally little affected by variations in wastewater flow and composition.
Phosphorus-recycling capability	3	Medium contains heavy metals in excess of soil background levels—may require dilution to meet EPA 503 regulations.
Maintenance requirements	3	BOF filter expected to last 15 to 20 years, peat filter will likely need replacement every 2 to 3 years.
Familiarity to the user	5	No change in user behavior from standard septic system.
Weighted Score	3.9	

Table 2-15
Evaluation of Peatland™ System

Criterion	Score	Comment
Proven track record	3	Data obtained for four systems, five years in duration. More than 30 systems in operation in total.
Phosphorus-management capability	5	Greater than 90% initially, expected to decrease as filter becomes saturated.
Cost	1	For a single house, estimated installed cost $10,000; estimated life-cycle cost $23,000 to $27,000.
Robustness of system	5	Up to 1.5 times design flows have been observed with good treatment results; having a peat filter and a wetland in series provides double robustness.
Phosphorus-recycling capability	5	The manufacturer says it is possible to recycle the used peat from tree farms and other sources. Peat sorbent is frequently used in horticulture and is assumed to contain no toxic substances.
Maintenance requirements	3	Little other than replacement of peat filter after 20 years. Inspection once a year.
Familiarity to the user	5	No change in user behavior from standard septic system.
Weighted Score	4.3	

Table 2-16
Evaluation of Nanoparticle Selective Resin

Criterion	Score	Comment
Proven track record	1	No data on P removal were presented, other than through personal communication. One site exists in Florida, data to be released by spring 2005.
Phosphorus-management capability	5	Potentially high removal capability. Site in Florida is achieving greater than 80%.
Cost	Too little data	$13,000 total installed cost for one system designed to treat over 50,000 gal/day of agricultural wastewater.
Robustness of system	4	Susceptible to interferences with anions such as arsenic, vanadium, uranium, and others.

Table 2-16
Evaluation of Nanoparticle Selective Resin (Cont.)

Criterion	Score	Comment
Phosphorus-recycling capability	5	Phosphorus fertilizer can be produced through chemical precipitation of the regenerate.
Maintenance requirements	No data	Largely unknown. Too early in technology's development.
Familiarity to the user	1–5	No change in user behavior from a standard septic system for a cluster system. For one technology, training and licensing in handling caustic chemicals is required of the operator—this is invisible to the user in a cluster system but highly demanding for an onsite system.
Weighted Score	N/A	Too little data to meaningfully compare with others.

Table 2-17
Evaluation of Extended-Aeration Activated Sludge

Criterion	Score	Comment
Proven track record	4	More than 67 units in operation; independent sources of data.
Phosphorus-management capability	5	Greater than 90% if dosage applied correctly; if dosage is too low, P removal drops considerably.
Cost	1	Estimated installed cost $9,700; total estimated life-cycle cost $44,000.
Robustness of system	2	P removal varies greatly in the same system over time.
Phosphorus-recycling capability	3	Similar issues that apply to the treatment of septage. The sludge contains 69 g P/kg (dry weight).
Maintenance requirements	1	Sludge removal required twice a year. System monitoring required for system to run properly.
Familiarity to the user	3	Regular checking of the system required to make sure it is running properly. Otherwise, no change in user behavior from a standard septic system.
Weighted Score	3.2	

Table 2-18
Evaluation of Sequencing Batch Reactor

Criterion	Score	Comment
Proven track record	5	3,500 treatment plants in operation; independent sources of data.
Phosphorus-management capability	5	70 to 80% if dosage applied correctly; if dosage is too low, P removal drops considerably.
Cost	1	Installed cost $11,000; total estimated life-cycle cost $37,000.
Robustness of system	2	P removal varies greatly in the same system over time.
Phosphorus-recycling capability	4	Sludge readily available for composting, contains 36 g P/kg dry weight sludge.
Maintenance requirements	2	Excess sludge is dried and can be easily removed, System monitoring required for system to run properly.
Familiarity to the user	3	Regular checking of the system required to make sure it is running properly. Otherwise, no change in user behavior from a standard septic system.
Weighted Score	3.7	

2.5 Soil Absorption System

The role of soil in onsite systems is to provide the area for dispersal of a large volume of effluent and to further treat the effluent before it reaches groundwater or surface water (Miles 1998; Sievers and Miles 1995). The permeability, structure, texture, aeration qualities, surface area, and vertical separation (soil thickness) from the infiltrative point of dispersal in the soil will influence the contaminant removal and degree of treatment. However, Cuyk *et al.* (2001) stated that the major portion of pollutant removal was at 30 to 60 cm for many contaminants. Phosphorus removal within the soil occurs through plant uptake by vegetation on or near the soil absorption system (SAS), biological immobilization, and precipitation and sorption processes in the soil (Reneau *et al.* 1989). Robertson and Harman (1999) found that P accumulation and concentration tended to take place close to the effluent dispersal components of the SAS. They referred to this area of attenuation as the “Phosphorus Rapid Transformation Zone.”

Lombardo *et al.* (Submitted) developed a handbook on the present understanding of phosphorus geochemistry relative to removal in the septic tank, SAS, and groundwater away from the SAS. The removal of phosphorus from the wastewater stream is primarily governed by adsorption and mineral precipitation. They further summarized that phosphorus removal in the SAS centers on mineral precipitation through Fe and Al (aluminum) precipitates which are influenced by pH, Fe, and Al solubility and redox conditions. Lombardo *et al.* also included the work of Robertson *et al.* (1998) showing that soil, wastewater, and site properties strongly influence the retention of phosphorus in the vadose zone in that a wide range of phosphorus retention (23 to 99%) can occur.

Phosphorus removal from wastewater can be an important treatment element in many receiving environments. This removal is particularly important for systems near surface waters, as elevated phosphorus levels can lead to eutrophication in lakes and rivers. Typical concentrations of phosphorus in domestic septic tank effluent range from 12 to 20 mg/L (Crites and Tchobanoglous 1998), but in recent years, some regulatory authorities have enacted phosphorus limits as low as 0.5 mg/L for specific receiving environments. If the phosphorus in septic tank effluent is not reduced by treatment before dispersal, the soil is the only component that can treat the effluent before it enters a water body. Robertson *et al.* (1998) reported P removal in ten mature SASs in Ontario to be quite diverse, with decreases from 23% to nearly 99%.

Phosphorus is an essential element for plants, which can be used to extract phosphorus from soil and store it in their biomass. The background concentration of phosphorus in soils worldwide ranges from 0.001 mg/L to nearly 1 mg/L in soil water solutions (Brady and Weil 2002). Soil pH is a strong influence on the anionic species of phosphate available. At acidic pH values of 4 to 5.5, the monovalent anion (HPO_4^{-1}) is dominant while the divalent phosphate anion ($H_2PO_4^{-2}$) is dominant at pH values from 7.5 and above (Brady and Weil 2002). At near-neutral soil pH conditions, both phosphorus species are nearly equal in abundance and availability to plants. To improve phosphorus removal by plants, it is critical to remove the aboveground biomass from the SAS area. Continued cyclic additions of plant biomass will maintain or increase the phosphorus in surface soils through natural recycling processes. The use of plants to enhance phosphorus removal is discussed in Section 2.6.

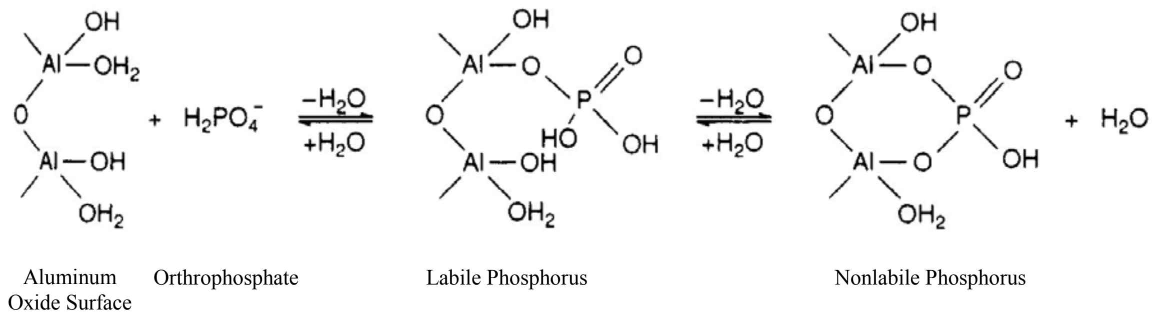
2.5.1.1 Soil Chemistry and Phosphorus Removal

A fundamental understanding of soil chemical, physical, and biological properties is important to understand the removal of phosphorus by soil. Phosphorus in most domestic systems is comprised of orthophosphates, polyphosphates, and insoluble phosphates (Manahan 1994) with orthophosphates comprising up to 80% of the total (Reneau and Pettry 1975). Phosphorus precipitation and sorption mechanisms in soils may include an ion exchange capacity, chemisorption (Figure 2-13), surface precipitation, precipitation as a solid mineral species, and physical adsorption (Brady and Weil 2002; McBride 1994). Many authors refer to the phosphorus adsorption and precipitation potential of soils as the phosphorus-fixation capacity of the soil (Brady and Weil 2002). Much of the potential for phosphorus fixation centers on other chemical properties of the soils (Brady and Weil 2002; McBride 1994; Sanchez and Uehara 1980):

- pH
- Soluble Ca (calcium)
- Fe (iron)
- Al (aluminum) content

- Calcium carbonate content
- Organic matter content
- Content of oxides and hydrous oxides of iron and aluminum

Surface area and the degree of crystallinity (the packing together of atoms in a repeating manner to form a three-dimensional pattern) of potential phosphorus-fixing solid particles also have a modifying influence on the strength of phosphorus fixation.

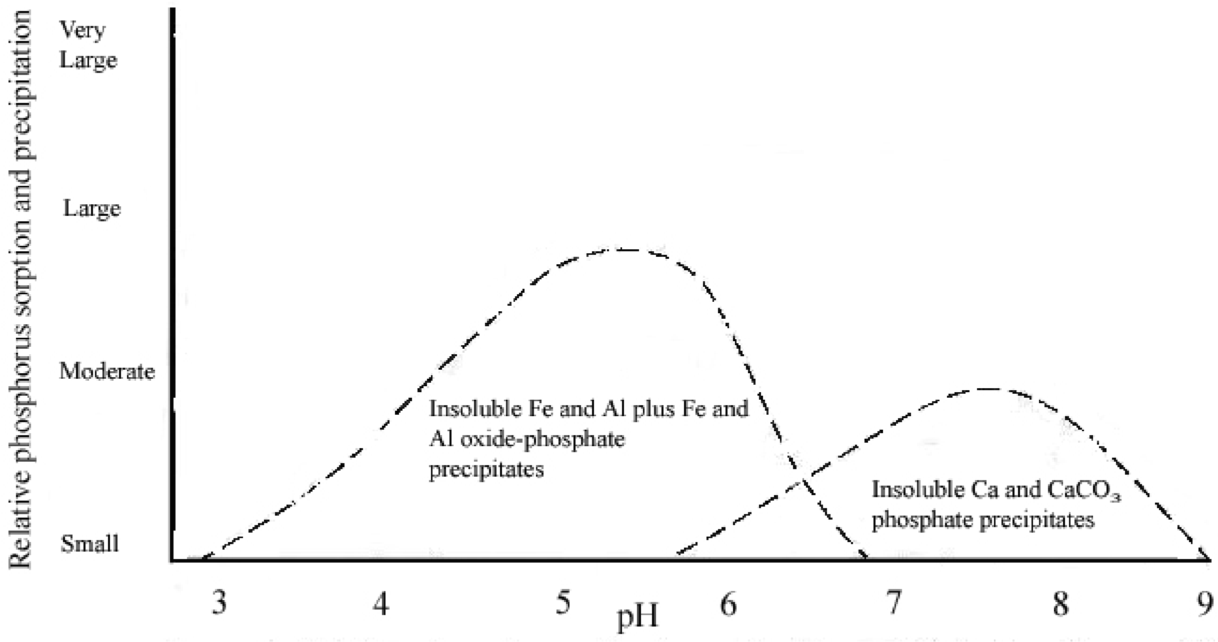


Adapted from Tisdale *et al.* (1993).

When two AL-O-P bonds with orthophosphate occur, the P is considered to be chemisorbed (nonlabile).

Figure 2-13
An Example of the Mechanism of Phosphorus Adsorption When an Effluent Orthophosphate is Bonded Through One Al-O-P Bond Providing Labile P

Soil pH has a dominant influence on phosphorus fixation. At high pH values (alkaline soils), calcium tends to be dominant in soil solution, and insoluble Ca-P complexes can be formed (Figure 2-14). At pH values less than five (acidic), iron, aluminum, and manganese are highly soluble. These cations have a great affinity for phosphorus and can also form insoluble complexes (McBride 1994; Sanchez and Uehara 1980). Flooding may also influence phosphorus fixation in soils. Changes in soil pH with flooding can alter the solubility of various Al-P and Fe-P complexes in acid soils. Phosphorus fixation can slightly decrease with flooding because of the change of ferric iron to the more soluble ferrous hydrous oxides during reduction (Sanchez and Uehara 1980). However, the overall potential for phosphorus fixation does not appear to change significantly (Sanchez and Uehara 1980).



Adapted from Tisdale *et al.* (1993)

Figure 2-14
Relative Phosphorus Fixation With pH

Soils that contain excess calcium and discrete masses of calcium carbonate have a moderate to large capacity to adsorb phosphorus onto the surfaces of calcium carbonate particles (Brady and Weil 2002). Of greatest phosphorus-fixation potential, however, are the Fe and Al oxides and hydrous oxides, especially when these colloids are amorphous or weakly crystalline. This less crystalline property provides greater surface area and thus great potential for contact and exposure to dissolved phosphorus (Sanchez and Uehara 1980). In soils with large amounts of mineral oxides and hydrous oxides, phosphorus fixation may be decreased with increasing organic matter content. Lombardo *et al.* (Submitted) summarized that the most comprehensive phosphorus removal occurs in soils that are acidic (do not contain carbonate minerals) and in wastewater with oxidation of organic carbon and ammonium. They further state that less effective phosphorus removal occurs in soils that contain carbonates in which the acidity from the oxidation reactions is rapidly buffered, thus providing near-neutral pH values. It is thought that the organic radicals block the hydroxyl sites on the oxide and hydrous oxide surfaces, thus lowering the possibility for contact of these hydroxyl sites to phosphorus in solution (Fox and Kamprath 1970).

Anion exchange capacity (AEC) is the ability of the soil to retain and exchange anions. Phosphorus, in the form of the phosphate anion, can be affected by AEC. Much of the AEC in soils is due to the presence of kaolinite clay and iron and aluminum oxides (Brady and Weil 2002; McBride 1994). The soils with the greatest AEC are highly weathered soils in the humid tropics. The dynamic nature of retention and exchange in this process, through the flux of other anions in the soil environment, may provide competition for sites in soils with small AEC. In most North American soils, AEC does not have great potential for phosphorus retention.

In summary, the phosphorus-fixation potential of a soil material is a function of the number and accessibility of sites that have the potential to sorb phosphorus. The predominant soil qualities that influence this potential are particle size and pH. As a general rule, soils with finer particles have greater surface area available for contact with the soil solution or effluent, and thus have greater potential to fix phosphorus. From a soil compositional and mineralogical aspect, increasing soil phosphorus fixation occurs as one moves from 2:1 silicate clays to 1:1 silicate clays, to oxides, and then to hydrous oxides of Fe and Al (Brady and Weil 2002). Within the oxides and hydrous oxides of Fe and Al, the capacity for phosphorus fixation increases with decreasing crystallinity; amorphous material possesses the greatest phosphorus-fixation potential. Decreases in pH provide increased soluble Fe and Al, which can form insoluble complexes with phosphorus. As pH increases above seven, soluble Ca will increase and insoluble complexes may also be formed.

2.5.1.2 Phosphorus Removal In and Near the Soil Absorption System

The phosphorus-fixation potential of a soil is finite. If phosphorus is added to the soil over a long period, its phosphorus-fixation potential can be exhausted. Furthermore, many assessments of effluent phosphorus-fixation in soils are based on hypothetical calculations or relatively short-term data. An example calculation was performed for an assumed homogeneous soil having septic tank effluent of 10 mg/L of soluble phosphate at a daily flow of 600 L over a 70 m^2 area (McBride 1994). The sorption capacity of the soil was estimated to be 200 mg P/kg soil. The calculations predicted that the phosphate would have moved no deeper than 1 m over 10 years, but no field validation was conducted.

A laboratory soil column study found that phosphorus-sorption capacities of soils varied more than three-fold, but in a separate field study, soils surrounding SASs up to 15 years old were not completely saturated with phosphorus (Sawhney and Hill 1975). The authors also confirmed in the laboratory that phosphorus-sorption sites in soils may be regenerated over time, especially after wetting and drying cycles. Phosphorus-removal rates of 90% were found in laboratory soil column and field studies of a weakly crystalline, Al- and Fe-rich Andisol soil (Kimochi *et al.* 2004). A laboratory column study where effluent was added to columns containing 20 different soils found that little phosphorus removal was obtained when the soil was coarse textured or had quartz mineralogy; however, up to 95% phosphorus removal was obtained in soils containing significant oxides or kaolinite (Al-Shiekh Khalil *et al.* 2004). Contrastingly, soil columns containing primarily shrink-swell clays had relatively low phosphorus removal.

Phosphorus contamination in SAS field studies is generally limited to shallow groundwater, with phosphorus fixation continuing under saturated conditions (Reneau *et al.* 1989). Field studies near SASs show that many soils are capable of sorbing much of the effluent phosphorus. In a field study of a Paleudult soil after 15 years of receiving wastewater effluent, fixation primarily occurred in the soil's Al-P and Fe-P complex fraction (Reneau and Pettry 1976). Movement of effluent within the soil landscape had not appreciably altered soil phosphorus concentrations more than 3 m away from the SAS. An evaluation of spray irrigation using onsite wastewater effluent on marginal soils found that the surface soil materials removed 96% of the effluent phosphorus, and that irrigation did not result in increased phosphorus levels in the surface soil (Monnett *et al.* 1996). Increased phosphorus transport is more likely in coarser textured soil conditions where there are few oxides of Fe and Al, where uniform effluent distribution is not achieved, and where effluent flow is rapid away from the SAS (Reneau *et al.* 1989; Geary 2004). Saturated flow conditions may also result in the migration of effluent phosphorus beyond predicted distances in poorly drained locations (Reneau 1979).

The phosphorus sorptive capacities of soil sources and industrial solid wastes as possible amendment materials for SAS have also been investigated. Isotherm studies indicated that red mud gypsum, alkaline fly ash and a local soil source (Merribrook loamy sand) provided high phosphorus removal (Cheung *et al.* 1994). The loamy sand performed better at low phosphorus concentrations. Bottom ash and acidic fly ash possessed low phosphorus-fixation potential. Further assessment through column and field studies is necessary to provide a realistic approximation of these materials' utility in SAS (Cheung *et al.* 1994).

2.5.2 Potential for Further Phosphorus Removal

The SAS and the soil are the last components of the onsite system (Miles 1998). Thus, proper soil and site characteristics, assessment of design parameters, and maintenance of the SAS are important to long-term phosphorus removal.

The first consideration should be in the soil and site selection process. Until recently, little emphasis was placed on phosphorus removal by onsite systems, and consequently phosphorus removal has not been considered an important treatment component of the soil. Where phosphorus removal is an important criterion for siting and designing the SAS, the soil properties that enhance removal should be of prime consideration. Soil properties such as moderate to fine texture, acidic or alkaline pH, and relatively high oxide and hydrous oxide content should receive strong consideration.

In many soil/site assessment codes or protocol, soil texture is already part of the standard soil description (Miles 1998). In many cases, the soil/site evaluator already needs to know the geographic/physiographic area and the associated clay mineralogy relative to shrink-swell potential in order to make siting and loading rate assessments. Additional knowledge of oxide and hydrous oxide occurrence in these physiographic areas would be of great assistance.

Soil color from the Soil Munsell color charts can be utilized to infer the phosphorus-fixation potential of the soil. This utilization can be part of the comprehensive soil/site assessment that provides field evaluation of soil parameters that are indicators of phosphorus fixation. Specific colors of the 7.5YR and redder hues generally indicate soil material that has greater phosphorus-fixation potential than other color hues. Additionally, descriptions of soil structure and associated soil porosity provide a rough assessment of effluent flow in the soil. Macropores may result in bypass flow, while flow in smaller soil pores provides greater effluent-soil particle contact.

Table 2-19 shows an example of a table that could be developed for use in site evaluation. The table helps assign points to different soil characteristics that affect phosphorus removal. Points are accrued for features that indicate more phosphorus-sorption capacity. Soil horizon thickness is used in conjunction with presence or absence of each feature to assign points to the soil profile. For example, a 10-inch thick B1 horizon is to be scored in the table. If it has a moderate to fine texture, $10 \times 3 = 30$ points are assigned for that feature. If the mineralogy is quartz, then $10 \times (-2) = -20$ points are assigned on that line. Sites with higher scores have higher phosphorus-sorption capacities. (Table 2-19 is an example of the beginnings of what such a method might look like. Much work on developing the table and its interpretation needs to be done before the method is ready for use.)

Table 2-19
An Example of a Table Assigning Points in the Field to Some Soil Morphological Site Characteristics That Affect Phosphorus Removal

Horizon and Thickness	Property and Points per Inch of Horizon Thickness	Points for This Site
B1, 10 inches	Texture moderate to fine +3	30
	Mineralogy kaolinite clay and pH less than 5.5 +2	
	Mineralogy quartz -2	-20
	Hue 7.5 YR +2 (if color value and chroma greater than 3)	
	Hue 5 YR +3 (if color value and chroma greater than 3)	
	Hue 2.5YR +4 (if color value and chroma greater than 3)	
	Hue 10R +5 (if color value and chroma greater than 3)	
Subtotal for horizon		10

In use, a table like this would be used for each of the horizons at or below the bottom of the soil absorption system, and the points tallied after the soil profile evaluation was complete.

At some sites, naturally-occurring soil properties do not provide sufficient phosphorus removal. Therefore, other design and management tools must be provided.

The geometry of the SAS can be critical for maximization of the soil's phosphorus-fixation potential (Sawhney and Hill 1975). Soil absorption beds, where length and width are somewhat equal, provide less soil surface area exposure than long, narrow trenches where length is considerably greater than width (Figure 2-15). The major difference between these two designs is increased area in the sidewalls of the trenches that provides additional surface area for treatment. As the soil surface area contact increases, the possibility that the effluent will contact soil particles with the potential to fix phosphorus also increases. However, sidewalls are only effective if ponding occurs in the SAS.

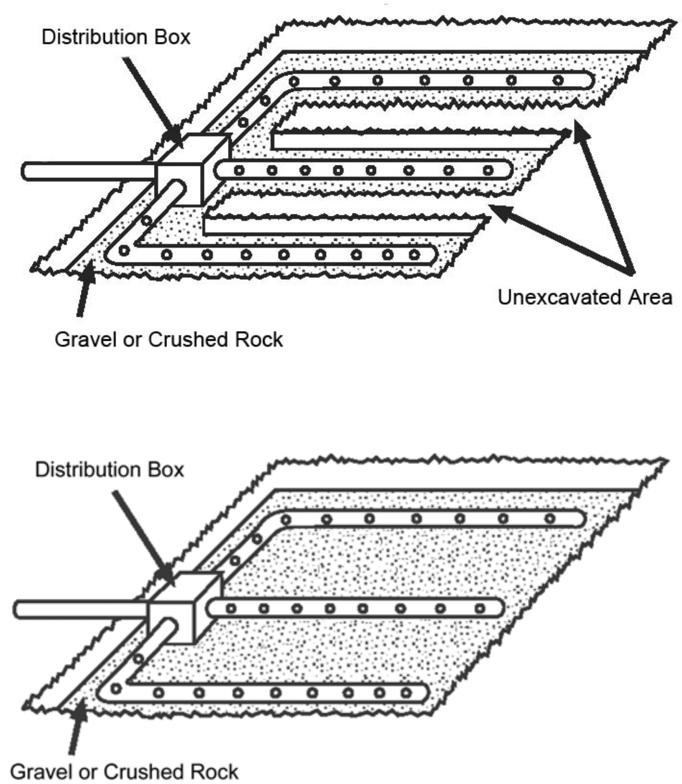


Figure 2-15
Leachfield Trenches (upper) and a Leachbed (lower) for Distributing Effluent

A shallow SAS should also increase phosphorus removal through plant uptake, as the largest volume of plant roots is near the surface. The roots need to be in contact with effluent as it passes in the soil. Holden *et al.* (2004) found that most of the grass samples collected from shallow, narrow leachfields possessed greater above-ground biomass and more total phosphorus in the biomass of unfertilized home lawns than the control areas. Additionally, in most of the shallow, narrow leachfields, they observed larger total phosphorus concentrations in the soil below the trench that they suggested was a result of soil sorption. Plant uptake should be better using drip distribution, because it is placed shallow in the soil profile and in the root zone, than in a trench where roots do not have much access to effluent. Increased phosphorus removal would also occur if the biomass of plant cover on the SAS were regularly harvested and removed from the site. Management is the key to removal of phosphorus, and biomass removal over shallow SAS is a key component of management. Still greater phosphorus removal could be attained if plant species (especially turf grass hybrids) with greater phosphorus nutritional needs were commercially available for use with SAS.

Delivery and application methods of effluent to the SAS from the septic tank or treatment train should be designed to maximize the effectiveness of phosphorus removal within the SAS. Ideally the effluent should have maximum contact with mineral soil components with phosphorus fixation capacity. Drop boxes can provide concentrated flow and accelerate the formation of “clogged” trenches, which helps expose sidewalls and shallow roots to effluent. This gives better management to enable resting, oxidation-reduction processes, and to control biomat. Conventional gravity distribution provides distribution "on demand." Since most residential usage is not uniformly distributed over a 24-hour period, saturation of the infiltrative surface of the SAS is possible. Gold and Sims (2000) expressed the concern that excessive loading under saturated flow could promote localized saturated flow of water and intrusion of nutrients into the vadose zone such that the chemical and biological removal capacity of the soil can be exceeded. Timed, pressure dosing can prevent localized saturated flow while promoting formation of a biomat. This uniform application might be a mechanism that can overcome the shortcomings of a gravity system with regard to removal of phosphorus.

Timed, pressure dosing has additional advantages when the SAS is placed within subsoils that contain clay films, or argillans. These argillans are zones of translocation of clay and other fine-textured constituents downward and (in some cases) laterally within the soil profile. These features indicate a relatively easy flow path of water through larger pores within the soil matrix (Buol *et al.* 1980). It is common for clay films to contain oxides of Fe and Al as well as organic components (Buol and Hole 1959); thus, clay films lining these pores have a high potential for phosphorus fixation. Because of the larger size of these pores, however, bypass flow of water and effluent may occur during saturated conditions, lowering the effectiveness of the argillans to fix phosphorus. Delivery and distribution of effluent within the SAS as unsaturated flow in a timed, pressure-dosed (shallow-placed) distribution system such as low-pressure pipe (LPP) distribution or drip dispersal will assist in maximizing the phosphorus-removal potential of the argillans lining the pore walls by providing contact to a greater volume of effluent, as well as a greater contact time with these Fe- and Al-rich features.

Using alternative materials during construction can also increase the phosphorus-removal capabilities of the SAS. Crushed limestone rock could be used within the conventional "gravel and pipe" trench to provide a medium with phosphorus-fixation surface area. A relatively small and finite phosphorus-removal capacity would be provided because of the medium's large particle size. The longevity of the phosphorus fixation is a primary consideration for this medium.

Rubber tires chipped to the specifications of the gravel medium could also be used in SAS construction. This medium was assessed under field conditions and in laboratory column studies to lower the phosphorus content in subsurface-flow constructed wetlands (Richter and Weaver 2004). However, the size of the aggregate chips and the amount (surface area) of wire exposed could limit the total phosphorus-fixation capacity with this medium. A number of states limit the amount of wire exposed to a half inch (Grimes *et al.* 2003), which could be counterproductive from a phosphorus-fixation perspective. Tire chips are inexpensive, have a low density and high pore space, and are abundant in many localities (Richter and Weaver 2004; McKenzie 2003; Grimes *et al.* 2003). Phosphorus removal in this medium occurs when the Fe of exposed wires in the steel-belted tire source form insoluble Fe-P compounds when exposed to effluent phosphorus. As with the limestone gravel medium, particle size and limited steel wire exposure would provide a finite phosphorus-removal capacity. Because the steel strands in tire chips have a smaller surface exposure than the total limestone gravel surface area, the tire chip component has a smaller total phosphorus-fixation capacity.

Additional SAS modifications to increase the phosphorus-removal efficiency of the soil should be assessed. The modifications should provide a medium, either in conjunction with or in lieu of gravel, which increases phosphorus-fixation potential on a long-term basis while also maintaining a loading rate that adequately disperses effluent. The ideal material must have a high potential to fix phosphorus, a large surface area to provide a relatively inexhaustible removal time frame, and must maintain the physical characteristics that enable effluent flow through the material and into the infiltrative soil surface. Sandy materials with the appropriate mineralogical composition (calcite or iron and aluminum oxides), as are used in many sand-lined trench designs, may have the best potential.

Many of the materials already evaluated have adequate phosphorus-fixation potential but do not have the physical properties (primarily particle size and shape) needed for effluent movement. Mixing the native soil around the SAS with materials that have proven phosphorus-removal potential, such as fly ash, red mud neutralized with gypsum, bottom ash, and transported soil with phosphorus-fixation qualities (Cheung *et al.* 1994; Wang and Sievers 2004), should be explored. “Doping” the SAS, through lining or sequential mixing of the phosphorus-fixation material within the infiltrative surface of native soil during construction, could provide increased phosphorus fixation using an expensive or limited-supply soil amendment while maintaining most of the soil’s integrity for effluent dispersal. This concept would be more expensive and would require increased labor and time for installation. The process also must be performed under dry soil conditions to minimize the degradation of soil physical properties and provide thorough mixing.

Assessment of a variety of siting, design, construction, and management factors is imperative to understanding the potential and effectiveness of long-term phosphorus removal within the SAS. Performance-based site assessment criteria have been proposed in some of the recent model codes. Development of soil and site assessment criteria to determine the native phosphorus-fixation potential should be the initial phase of the process, especially if land area is not a confining factor. The utilization of phosphorus-fixation materials, such as limestone gravel, rubber tire chips from steel-belted tires, or other coarse-textured material which has phosphorus-sorption capabilities within the SAS may be practical, but may not provide enough long-term fixation potential. Finer-textured materials such as fly ash or harvested soil with high iron oxide content may be used to line or “dope” the SAS infiltrative surface, as long as the hydraulic properties of the SAS are not impaired. Finally, dispersal methods such as LPP distribution or drip dispersal that provide unsaturated flow and increase soil/effluent contact and total contact time will maximize long-term total phosphorus fixation. The possible wetting and drying of the soil material during unsaturated flow conditions may assist in the regeneration of phosphorus-fixing sites in the surrounding soil material, but would appear to be minimal over time.

Additional characterization of the fixation of various phosphorus species from wastewater effluent by various soil components within the SAS should be conducted. The solubility of organic phosphorus species, as was recently found in long-term manured plots, should also be investigated in greater detail (Motavalli and Miles 2002). These baseline characterizations may provide greater knowledge of biological phosphorus availability; longevity of phosphorus compounds in the soil system; the stability of phosphorus species relative to reactivity and uptake by biological components (primarily plants); and the chemisorption potential from phosphorus species to other phosphorus species over time, resulting in greater ability to enhance the phosphorus-fixing efficiency of the soil and SAS.

In summary, a large amount of the phosphorus removal within the soil component of the SAS is through precipitation of Fe and Al phosphates (Lombardo *et al.* Submitted) in the “envelope” of soil immediately surrounding the placement of effluent in the soil (the “rapid transformation zone” described by Robertson and Harman 1999). Soil pH, Fe and Al oxide content, soluble Fe and Al content, soluble Ca content, calcium carbonate content, organic matter, and clay content all have a strong influence on phosphorus precipitation and adsorption. Soil attributes such as particle size and soil structure strongly influence the degree of saturated and unsaturated flow, the rate of flow as well the amount and length of contact with phosphorus-fixing mineral components; all of these influence the attenuation of phosphorus near the point of placement as well as any possible movement of phosphorus via bypass flow or movement of plumes from the SAS.

2.5.3 Methods

Based on the above discussion, seven methods for augmenting phosphorus removal in the SAS were evaluated:

- Comprehensive site assessment
- Added materials in SAS for “doping”
- Timed, pressure dosing with drip distribution
- Design of long, narrow trenches with effluent directed to a trench to pond it
- Narrow, shallow soil absorption systems
- Replacement of gravel in trench with tire chips
- Replacement of gravel in trench with limestone

2.5.4 Evaluation

The following tables indicate how the team scored the methods evaluated. An explanation of the scoring is in section 1.5.2.

The data sources used for the following evaluations were all assigned a High or Medium confidence level, using the scale developed as part of this project’s QAPP. For more details on the QAPP, the data sources, and the assignment of confidence levels, see Etnier *et al.* (2005).

Table 2-20
Evaluation of Comprehensive Site Assessment

Criterion	Score	Comment
Proven track record	4	Site testing has a long history, but not for phosphorus-fixation capacity.
Phosphorus-management capability	3	A function of the soil/site properties. Possibility of up to 90% removal over many years. Will provide definitive screening of sites with and without P-fixation potential.
Cost	5	Cheapest management strategy to employ.
Robustness of system	5	Works in a variety of site settings. Spikes in loading not applicable.
Phosphorus-recycling capability	1	Little recycling except by plants in soil absorption system.
Maintenance requirements	5	No maintenance required.
Familiarity to the user	5	No change in user behavior from conventional septic system.
Weighted Score	4.7	

Table 2-21
Evaluation of Added Materials in SAS for "Doping"

Criterion	Score	Comment
Proven track record	2	The effects of the material are well-characterized, but the technique has not been used much.
Phosphorus-management capability	3	High in the beginning but limited long-term capacity.
Cost	3	Limited availability in some areas; transportation costs.
Robustness of system	3	Expected to handle spikes in flows well, but limited long-term capacity.
Phosphorus-recycling capability	1	Little recycling.

Table 2-21
Evaluation of Added Materials in SAS for "Doping" (Cont.)

Criterion	Score	Comment
Maintenance requirements	3	Replacement of material may be needed over the long term.
Familiarity to the user	5	No change in user behavior from conventional septic system.
Weighted Score	3.3	

Table 2-22
Evaluation of Timed, Pressure Dosing With Drip Distribution

Criterion	Score	Comment
Proven track record	5	Used to assist in management of physical, chemical, and biological properties of the soil and SAS.
Phosphorus-management capability	4	Provides increased efficiency of P-fixation potential within SAS.
Cost	1	Installed cost alone can be $10,000.
Robustness of system	3	Used in a wide variety of situations to increase efficiencies in marginal soil and site situations.
Phosphorus-recycling capability	2	Recycling possible only at soil absorption system.
Maintenance requirements	2–3	Can be one of the most intensive systems. Semi-annual to annual inspection and flushing of the systems is required for some systems.
Familiarity to the user	5	No change in behavior from conventional septic system.
Weighted Score	3.6 – 3.8	

Table 2-23
Evaluation of Design of Long, Narrow Trenches With Effluent Directed to a Trench to Pond It

Criterion	Score	Comment
Proven track record	4	Long, narrow trenches used for decades; improved phosphorus-removal capability not well-documented.
Phosphorus-management capability	3	A function of the soil/site properties.
Cost	5	Where feasible, often less costly than beds.
Robustness of system	5	Works in a variety of site settings, handles loading spikes.
Phosphorus-recycling capability	1	Little recycling for reuse except by plants.
Maintenance requirements	5	No maintenance required if gravity fed. More maintenance required if pressure-dosed.
Familiarity to the user	5	No change in behavior from conventional septic system.
Weighted Score	4.7	

Table 2-24
Evaluation of Narrow, Shallow SAS

Criterion	Score	Comment
Proven track record	3	Used in many installations; improved phosphorus-removal capacity not well-documented.
Phosphorus-management capability	4	A function of soil/site properties. Increases amount of soil that effluent passes through, and placement in the root zone increases plant uptake.
Cost	5	Can be less costly than beds.
Robustness of system	3	Expected to handle spikes in flows well, but limited data.
Phosphorus-recycling capability	2	Improves possibilities for recycling at the SAS.
Maintenance requirements	4	Some vegetation management may be needed. Flushing of system if pressure dosed.

Table 2-24
Evaluation of Narrow, Shallow SAS (Cont.)

Criterion	Score	Comment
Familiarity to the user	5	No change in user behavior from conventional septic system.
Weighted Score	4.4	

Table 2-25
Evaluation of Replacement of Gravel in Trench With Tire Chips

Criterion	Score	Comment
Proven track record	2	Approved for use in North Carolina; little documentation of phosphorus-removal capacity.
Phosphorus-management capability	3	Apparently 25 to 70%, but no long-term performance data. Phosphorus-fixation capacity is finite.
Cost	4	Can reduce cost of aggregate 10 to 90% (Grimes *et al.* 2003).
Robustness of system	4	Expected to be comparable to gravel aggregate, but not documented.
Phosphorus-recycling capability	1	Little recycling.
Maintenance requirements	4	Removal of tire chips and replacement will be needed.
Familiarity to the user	5	No change in behavior from conventional septic system.
Weighted Score	4.0	

Table 2-26
Evaluation of Replacement of Gravel in Trench With Limestone

Criterion	Score	Comment
Proven track record	3	Used commonly in Missouri. P-fixation of limestone well-known, but few studies of this application.
Phosphorus-management capability	4	Probably quite high initially, but as the P-absorption sites are used, the P-fixation will decrease over the years. Limited data.

Table 2-26
Evaluation of Replacement of Gravel in Trench With Limestone (Cont.)

Criterion	Score	Comment
Cost	5	Comparable to gravel in many areas.
Robustness of system	5	Comparable to gravel.
Phosphorus-recycling capability	1	Little recycling.
Maintenance requirements	4	Removal of limestone and replacement will be needed at some point
Familiarity to the user	5	No change in user behavior from conventional septic system.
Weighted Score	4.5	

2.6 Biotic Sequestration of Phosphorus

2.6.1 History of Phosphorus Management Through Biotic Sequestration

Biological phosphorus sequestration from waste streams can be accomplished using microbes, algae, water-loving vegetation, and even terrestrial plants. In the septic tank and activated sludge processes, microbial uptake of phosphorus occurs in a way that allows the phosphorus to be removed from the system; they are not further discussed in this section. Aquatic plant systems have been shown to be effective as a secondary or tertiary stage for water treatment and nutrient management (US EPA 1999). Many different plant species and communities have been used as a part of wastewater treatment systems. The use of plants for wastewater treatment is a simple method that generally does not require costly machines and equipment or complex maintenance processes. It does, however, require large areas of land and a warm climate, and may require frequent harvesting to *maximize* phosphorus-sequestration potential. The frequent harvests for nutrient sequestration introduce both frequent maintenance and (for large-scale uses) expensive machinery to what is otherwise a simple method.

Examples of plants and plant communities used for wastewater treatment are many and varied. Floating macrophytes such as water hyacinth are used in lagoon systems in the southern US. Surface-flow and subsurface-flow constructed wetland systems planted with a variety of species are used to treat wastewater to secondary or tertiary quality, at scales ranging from single-family homes to greater than 100,000 gallons per day, throughout the US. This section provides a review of the organisms and communities for which phosphorus-sequestration data are available, and recommends areas for future research into phosphorus treatment.

Wetlands have probably been the most intensively researched method for biotic sequestration of phosphorus. Nichols (1983) reviewed the literature and argued that the major mechanism was not biological, but rather uptake in the soil. He showed a dramatic drop off in phosphorus-removal percentage as phosphorus loading increased, with removal of 68% at 1.5 g P/m^2/y, dropping to 47% at 6 g P/m^2/y, and further dropping from 30 to 20% between 20 and 80 g P/m^2/y. Brix (1994) reviews the performance of 174 wetlands and argues that peat accretion (accumulation of organic matter) is the most sustainable method of phosphorus removal in free-water-surface wetlands, and he also advocates a phosphorus removal unit using a substrate rich in iron or aluminum as the last stage in a wetland system. Breen (1990) ran a 50-day experiment comparing planted and unplanted wetlands in 10 L buckets and found that the planted wetlands outperformed the unplanted ones (95% versus 70% phosphorus removal) and that 39% of influent P was in the above-ground plant parts in the planted wetlands. This finding underlines the importance of harvesting plants to remove the nutrients from the system entirely.

2.6.2 Initial Screening of Phosphorus Management by Biotic Sequestration

More than 80 species and communities were initially screened for phosphorus-management capability based on a review of the available peer-reviewed literature. From those, plant species or biotic communities were selected for detailed evaluation based on the following criteria:

- Influent phosphorus concentration is both reported and is in the range characteristic of septic tank effluent in at least one study
- Phosphorus removal as a percentage of influent phosphorus is found to be 40% or greater in at least one study

A table containing the complete list of species screened and all data used in the initial screening is included in Appendix B. The plant species and biotic communities that met the initial screening criteria are:

- Periphyton
- Duckweed (Lemnaceae)
- Water Hyacinth (*Eichhornia crassipes*)
- Bulrushes (*Schoenoplectus* spp., a.k.a. *Scirpus* spp.)
- Cattail (*Typha* spp.)

Each of these is discussed in the following section.

2.6.3 Biotic Sequestration Evaluated in More Detail

The plant species and biotic communities that have the greatest capability for phosphorus removal fall into three categories:

- Periphyton
- Floating macrophytes (duckweed and water hyacinth)
- Emergent macrophytes (bulrushes and cattail)

A brief review of each of these categories as well as a description of the most promising commercially available methods in each category is given in following subsections. Table 2-27 summarizes phosphorus-removal percentages and rates by species.

Table 2-27
Summary of Plant Species and Biotic Communities With Greatest Phosphorus-Removal Potential

Name	Influent P (mg/L)	% P Removal	P Removed (kg/Ha/Year)	P as % of Organism's Dry Weight	Reference
Periphyton	12	98	N/R	N/R	Jackson and Jackson 1972
	N/R	>90	N/R	N/R	Hemens and Mason 1968
	5	76	N/R	N/R	Bush *et al.* 1963
	3.1	48	1,600	1.83	Craggs 2001
Duckweed (Lemnaceae)	1.3–14.3	50–99	N/R	0.3–1.4	Korner and Vermaat 1998
	15	31–96.7	N/R	N/R	Obek and Hasar 2002
	N/R	60–92.2	N/R	N/R	Hammouda *et al.* 1995
	4.1	74–92	N/R	N/R	Zimmo *et al.* 2002
	N/R	12–92	N/R	N/R	Oron *et al.* 1984
	N/R	30–50	N/R	1.5	Leng 1999
	13	11–43	N/R	N/R	Nhapi *et al.* 2003
	N/R	16	220	0.8–1.8	Reed 1995
	N/R	N/R	600	N/R	Culley Jr. and Myers 1980
Water Hyacinth (*Eichhornia crassipes*)	N/R	N/R	1,350	0.8	DeBusk 2001
	N/R	N/R	350–1,125	N/R	Reddy and DeBusk 1987
	N/R	N/R	896	0.4	Tourbier 1976
	10	90	0.5–5	N/R	Reddy and DeBusk 1987
	N/R	74–87	N/R	N/R	Tourbier 1976
	1.95	85	N/R	N/R	Cloris and Aruajo 1987
	1.46	81	169	N/R	DeBusk 2001
	2.6–5.8	35–80	N/R	N/R	NASA/NSTL 1980

Table 2-27
Summary of Plant Species and Biotic Communities with Greatest Phosphorus-Removal Potential (Cont.)

Name	Influent P (mg/L)	% P Removal	P Removed (kg/Ha/Year)	P as % of Organism's Dry Weight	Reference
Water Hyacinth (*Eichhornia crassipes*)	0.3	67	180	N/R	DeBusk 2001
	0.74	53	296	N/R	DeBusk 2001
	1.06	48	519	N/R	DeBusk 2001
	3.44	1–43	N/R	N/R	NASA/NSTL 1980
	6.12–6.66	38	N/R	N/R	NASA/NSTL 1980
	4.70–8.24	8–29	N/R	N/R	NASA/NSTL 1980
	4.74–6.72	10–23	N/R	N/R	NASA/NSTL 1980
	4.74–6.18	3–23	N/R	N/R	NASA/NSTL 1980
	4.33	21	N/R	N/R	NASA/NSTL 1980
	4.74–6.72	4–19	N/R	N/R	NASA/NSTL 1980
	4.33	14	515	N/R	DeBusk 2001
	4.68	10	113	N/R	DeBusk 2001
Bulrush (*Schoenoplectus*, a.k.a. *Scirpus* spp.)	N/R	7–93	N/R	N/R	Tanner 1994
	N/R	79–90	N/R	N/R	Soto *et al.* 1999
	1.28	50	N/R	N/R	Coleman *et al.* 2001
	N/R	35	N/R	N/R	Soto *et al.* 1999
	15	9–14	486	N/R	Tanner *et al.* 1999
Cattail (*Typha* spp.)	N/R	63–96	N/R	N/R	Mander *et al.* 2000
	52	96	N/R	N/R	Schaafsma *et al.* 2000
	1.28	80	N/R	N/R	Coleman *et al.* 2001
	74.81	30–45	33–39	N/R	Reddy *et al.* 2001
	N/R	N/R	65	0.25	Bernard 1999

N/R = Not Reported.

2.6.3.1 Periphyton

Periphyton is a complex matrix of algae and heterotrophic microbes attached to submerged substrata in almost all aquatic ecosystems. In addition to adsorbing phosphorus directly, periphyton can influence water chemistry at the sediment-water column interface by increasing the pH of water near the algal mat, and by supersaturating the interface with dissolved oxygen (Dodds 2003; Vaithiyanathan and Richardson 1998). If sufficient calcium, magnesium, or other polyvalent cations are also present, these conditions generally encourage the precipitation of calcium phosphate as part of an algal mineral complex (Hoffmann 1998). This mechanism, called autoflocculation, lowers phosphorus concentrations and aids in the removal of suspended algae from effluent. Algal treatment of wastewater, mediated through a combination of nutrient uptake, elevated pH, and high dissolved oxygen concentration can offer an ecologically safe, less expensive and more efficient means to remove nutrients than conventional tertiary treatment (Hoffmann 1998).

Periphyton-based systems have been in use in warm climates for more than 40 years and generally obtain phosphorus-removal rates of 48 to 98%. Light availability, the chemistry of the influent wastewater, and harvesting frequency and schedule must be closely controlled for optimal phosphorus removal. The largest drawback for periphyton-based systems is the high ongoing expense of biomass harvesting and drying. Total construction and O&M costs for these systems can rival those of activated sludge facilities (Abassi 1987).

2.6.3.2 Floating Macrophytes

Duckweed

Duckweed (Lemnaceae) is most commonly used in sealed pond or lagoon structures in temperate to warm climates. Various species are native to much of the US, and it can survive at temperatures as cold as 1° to 3 °C (Wolverton 1986). In cold climates, duckweed plants overwinter by sinking to the bottom of ponds. *Lemna minor* is commonly used for wastewater treatment due to its extremely vigorous growth rate (Campbell and Ogden 1999). Several investigations have shown that duckweed-based systems can remove up to 99% of influent phosphorus from wastewater (Edwards 1980; Reddy and DeBusk 1985; Zirschky and Reed 1988; Alaerts *et al.* 1996; Zimmo *et al.* 2002). Phosphorus removal using duckweed is realized by biomass increase, not by increasing phosphorus percentage within biomass (Korner and Vermaat 1998; Korner *et al.* 2003), so frequent harvesting is necessary to realize significant phosphorus removal from these systems (Obek and Hasar 2002).

Water Hyacinth

Water hyacinth (*Eichhornia crassipes*) is a free-floating, perennial plant with buoyant leaves. Although it is best known as an invasive nuisance species, water hyacinth has been grown in lagoons to treat wastewater in the southern US. The primary use of water hyacinth for wastewater treatment has been at the centralized level (NASA/NSTL 1980), where it has been reported to remove as much as 90% of influent phosphorus. Water hyacinths grown under ideal climatic conditions will produce 70 tons of dry weight per acre annually (Wolverton 1986; Tourbier 1976), a significant amount of residual organic material. Potential uses for this material include methane gas production and animal feed (Bruce Undated.). The dried stems are also used in wicker furniture. Although these systems require frequent maintenance to achieve significant phosphorus removal, they generally cost less to construct and operate than conventional systems of similar size.

2.6.3.3 Emergent Macrophytes

Constructed wetlands, especially subsurface flow wetlands, are appropriate for northern climates, as wetlands will often remain active under the snow layer and can remain warmer than the surrounding frost layer due to microbial activity and warm influent. The plants contribute little to phosphorus removal during the winter, though substrate effects continue. Plant uptake of phosphorus in constructed wetlands is normally less than 10% of influent phosphorus (Crites and Tchobanoglous 1998). Planted wetlands are not as actively maintained as floating macrophyte systems and thus may have lower operation and maintenance costs.

Bulrushes

Nutrient retention features that are characteristic of natural wetlands can also be exploited in constructed wetlands. Plant species such as bulrushes (*Schoenoplectus* spp. and *Scirpus* spp.) are typically used in surface flow and subsurface-flow constructed wetland systems that treat wastewater (Tanner *et al.* 1999; Soto *et al.* 1999; Coleman *et al.* 2001). These systems have been reported to remove 7 to 90% of influent phosphorus (Coleman *et al.* 2001; Tanner *et al.* 1999), but the substrate in which rushes are planted has a significant impact on the efficacy of phosphorus removal. For example, only 9 to 14% total phosphorus removal was reported for the biomass of bulrush *Schoenoplectus tabernaemontani* following a two-year period of substrate equilibration in a gravel-bed constructed wetland (Tanner *et al.* 1999). In another constructed wetland planted with bulrushes, phosphorus retention was low (28%) and the effluent from the wetland system sometimes had higher phosphorus concentrations than the influent (Geary and Moore 1999). The possibility of phosphorus removal in these systems is finite due to saturation of the substrate.

Cattail

Cattails (*Typha* spp.) are typically used in subsurface-flow constructed wetland systems (Kadlec 1999; Mulamoottil *et al.* 1999). These systems have been reported to remove 30 to 96% of influent phosphorus (Coleman *et al.* 2001; Mander *et al.* 2000; Reddy *et al.* 2001). As discussed previously, the substrate medium may significantly affect overall phosphorus removal; however, cattails were not tested relative to an unplanted substrate in the studies evaluated for this report.

2.6.4 Evaluation

The following tables indicate how the team has scored the methods evaluated. An explanation of the scoring is in section 1.5.2.

For the reasons described in Etnier *et al.* (2005), data sources used in this section were not evaluated according to the project QAPP.

Table 2-28
Evaluation of Periphyton

Criterion	Score	Comment
Proven track record	3	Used for 40+ years; number of systems unknown.
Phosphorus-management capability	3	Reported range of 48 to 98%; harvesting schedule is primary determinant in efficiency.
Cost	1	Total costs rival those of activated sludge facilities.
Robustness of system	2	Does not function in cold climates (periphyton die off).
Phosphorus-recycling capability	5	Biomass is readily composted; does not generally concentrate heavy metals.
Maintenance requirements	1	Daily to weekly harvesting required for optimal performance; maintaining community succession requires careful attention.
Familiarity to the user	5	No change in user behavior from standard septic system (in cluster system applications).
Weighted Score	3.1	

Table 2-29
Evaluation of Duckweed

Criterion	Score	Comment
Proven track record	3	Used for 24+ years; number of systems unknown.
Phosphorus-management capability	2	Reported range of 11 to 99%; vigorous harvesting schemes (on the order of every 48 hours) needed to achieve high removal rates.
Cost		Not found. (Not used in weighted score).
Robustness of system	3	Temperature must remain above 1 °C; high temperatures may also be problematic.

Table 2-29
Evaluation of Duckweed (Cont.)

Criterion	Score	Comment
Phosphorus-recycling capability	5	Biomass is readily composted; high protein content makes it potentially suitable as livestock feed.
Maintenance requirements	1	Vigorous harvesting schemes (on the order of every 48 hours) needed to achieve high removal rates.
Familiarity to the user	5	No change in user behavior from standard septic system (in cluster system applications).
Weighted Score	3.3	

Table 2-30
Evaluation of Water Hyacinth

Criterion	Score	Comment
Proven track record	3	Tens to hundreds of systems in use; little data available on P removal for these systems.
Phosphorus-management capability	3	Reported range of 1 to 90% (average 41% from all available sources).
Cost		Not found. (Not used in weighted score).
Robustness of system	2	Relatively tolerant of low flows. Consider only in appropriate (warm) climates.
Phosphorus-recycling capability	5	Biomass can be composted for use as fertilizer; research underway to use biomass to generate methane; dried stems used in wicker furniture.
Maintenance requirements	1	Optimal harvesting may be as much as twice a week.
Familiarity to the user	5	No change in user behavior from standard septic system (in cluster system applications).
Weighted Score	3.5	

Table 2-31
Evaluation of Cattail

Criterion	Score	Comment
Proven track record	4	Thousands of systems in use, but P removal usually not primary goal of these systems.
Phosphorus-management capability	2	Reported range of 30 to 96%; substrate medium provides a significant portion of overall P removal.
Cost		Not found. (Not used in weighted score).
Robustness of system	3	Tolerant of flow variations, although plantings will not tolerate dry conditions. Biomass dies back in cold temperatures; P sequestered in rootstocks and in substrate only in winter.
Phosphorus-recycling capability	2	Biomass may be harvested and composted, but P in substrate likely cannot be recycled.
Maintenance requirements	2	Systems are generally more stable than floating macrophyte systems. Harvesting will occur less frequently but may still be a significant effort.
Familiarity to the user	5	No change in user behavior from standard septic system (in cluster system applications).
Weighted Score	3.3	

3 MOST PROMISING PHOSPHORUS-MANAGEMENT METHODS

In this study, five different approaches to phosphorus management were evaluated:

- Source reduction
- Source diversion
- Treatment in the septic tank
- Post-septic tank treatment
- Design of the soil absorption system

Within some of the approaches, the methods examined varied significantly. The methods were evaluated by applying seven criteria. Some of these criteria could be applied objectively, for example, over 80% phosphorus reduction rates a score of 5 on "Phosphorus-management capability" (see section 1.5.2). Some of the criteria are more subjective, such as, robustness of the system. Even those criteria that appear objective have some element of judgement in the scoring. How does one rate a method on phosphorus-management capability if studies have shown a substantial variation in the capability for one system, or if different studies have different results? An effort was made to apply subjective judgements similarly across all of the methods evaluated.

Excluding biotic sequestration methods, which span post-septic tank treatment and the soil absorption system and are discussed later, Table 3-1 shows the ranking of all methods by their overall weighted average scores. Where there was a range of scores (depending on different brands of the same general management method, for example), the highest was used.

Of all the criteria used, the least amount of information was found on phosphorus-recycling capability. Assumptions and inferences were made to score the methods for phosphorus-recycling capability, but there is too little information available on this aspect of most methods to make reliable judgements. To anchor the evaluations more firmly in available data, the phosphorus-recycling capability was excluded from the weighted average score (Table 3-2). The most promising phosphorus-management methods are the top ten methods listed in Table 3-2.

Table 3-1
Phosphorus-Management Methods (excluding biota) Ranked by Weighted Average Score

Rank	Method	Weighted Average Score
1	P-free laundry detergent	4.9
2	P-free dishwasher detergent	4.9
3	Microflush toilet	4.8
4	Eliminate garbage disposal	4.8
5	Comprehensive site assessment	4.7
6	Design of long, narrow trenches	4.7
7	Urine diversion	4.6
8	Aquatron	4.5
9	Lightweight aggregates	4.5
10	Limestone as SAS medium	4.5
11	Compost toilet	4.4
12	Shallow SAS	4.4
13	Peatland	4.3
14	PhosRID	4.0
15	Tire chips as SAS medium	4.0
16	Basic oxygen furnace (BOF) slag in a packed-bed filter	3.9
17	Timed, pressure dosing	3.8
18	Sequencing batch reactor	3.7
19	RUCK CFT	3.4
20	Doping SAS	3.3
21	Extended aeration activated sludge	3.2
22	Equaris Infinity	3.1
23	Alum injection	3.1

Table 3-2
Phosphorus-Management Methods (excluding biota) Ranked by Weighted Average Score Excluding Phosphorus-Recycling Capability

Rank	Method	Weighted Average Score Excluding P Recycling Capability
1	Comprehensive site assessment	5.3
2	Design of long, narrow trenches	5.3
3	Limestone as SAS medium	5.1
4	P-free laundry detergent	4.9
5	P-free dishwasher detergent	4.9
6	Shallow SAS	4.8
7	Eliminate garbage disposal	4.7
8	Lightweight aggregates	4.6
9	Microflush toilet	4.6
10	Tire chips as SAS medium	4.5
11	Urine diversion	4.3
12	Aquatron	4.3
13	Compost toilet	4.3
14	Peatland	4.2
15	Timed, pressure dosing	4.1
16	BOF slag in a packed-bed filter	4.0
17	PhosRID	4.0
18	Doping SAS	3.7
19	Sequencing batch reactor	3.6
20	RUCK CFT	3.4
21	Extended aeration activated sludge	3.2
22	Alum injection	3.1
23	Equaris Infinity	2.8

To determine the robustness of the rankings in Table 3-2, a sensitivity analysis was performed by removing each of the evaluation criteria in turn from the weighted average score. That is, instead of excluding "Phosphorus-recycling capability," each of the other criteria was, in turn, excluded. Table 3-3 shows the additional methods that made it into the top ten when various criteria were excluded from consideration. All of the methods listed in Table 3-3 ranked just below the top ten in Table 3-2. This finding indicates that the ranking shown in Table 3-2 is reasonably robust.

Table 3-3
Methods Not in the Top Eleven of Table 3-2 but Which Rank in the Top Ten When Other Criteria Are Excluded

Criterion Excluded From Consideration	Additional Methods
Proven Track Record	Aquatron; Peatland
Phosphorus-Management Capability	Aquatron; Urine diversion
Cost	Urine diversion; Aquatron; PhosRID; BOF slag
Robustness	Urine diversion; Aquatron
Maintenance Requirements	Urine diversion; Aquatron
Familiarity to User	Urine diversion; Compost toilet

Methods that use the soil absorption system comprise five of the top ten methods in Table 3-2. On many sites, significant phosphorus management can be achieved with a conventional septic system consisting of a septic tank and SAS. A comprehensive site assessment is performed to estimate the phosphorus-removal capability of the soil and find the best soils for phosphorus removal, and then the SAS is designed to maximize the phosphorus removal. If the soils native to the site provide little opportunity for phosphorus removal, no matter what the SAS placement or shape, then the SAS fill medium (tire chips, limestone, and other media) can provide high levels of phosphorus removal for a finite time.

All three source-reduction strategies are among the most promising methods for phosphorus management. This shows that a method does not have to affect large amounts of phosphorus to be a top scorer, if it excels in other areas. A dramatic example is that of eliminating the garbage disposal, which reduces phosphorus loads by only 3 to 10% and, where there is room for on-lot composting, costs little other than $100 for a couple of compost bins and the labor of maintaining a compost pile. Eliminating the garbage disposal may even save money by reducing the size of the septic system required—in Massachusetts, for example, the leachfield must be increased in area by 50% if a garbage disposal is to be used [(310 CMR 15.240(4)].

If phosphorus-recycling capability is included as a criterion, the microflush toilet system scores third, after two source reduction strategies. All the microflush toilets can divert around 75% of the phosphorus in domestic wastewater. The microflush vacuum toilets are the closest of all source diversion strategies to a conventional water toilet experience for the user, so they may be easiest to introduce. Added advantages include their great reduction of the nitrogen and organic matter content of the remaining domestic wastewater (the graywater) and their inherent ability to run the blackwater uphill, for example, inland at a lakeside residence. Their estimated added life-cycle cost of $35,000 to $40,000 may be a significant barrier; most of the ongoing costs come from emptying the holding tank three to five times a year.[2]

Lightweight aggregates in a packed-bed filter were the only post-septic tank medium to rank among the most promising methods. They can remove up to 99% of the phosphorus, and systems using versions of the product have been in place since the early 1990s.

Two other sorbent-based, post-septic tank methods that show excellent potential for phosphorus removal are PhosRID™ and BOF slag in a packed-bed filter. They rank in the top ten if costs are excluded from consideration. Since only a few systems are in place, there is little field experience with maintenance needs.

The urine-diverting toilet is not in the top ten, though it appears there in five of the six sensitivity test runs in Table 3-3. Urine-diverting toilets score a 2 out of a possible 5 on the "User Familiarity" scale, and they are only likely to gain acceptance if their introduction is accompanied by much user education and motivation. Still, when accepted and used, they offer a robust method for removing 33 to 43% of the phosphorus from domestic wastewater, at a life-cycle cost of around $10,000.

The Aquatron becomes one of the top ten in four of the six sensitivity test runs in Table 3-3. It has a relatively low phosphorus-removal capability (calculated at 13% or less), but it is a robust system with either a relatively low cost (if the user empties the compost) or a high degree of familiarity to the user (if there is a maintenance contract to empty the compost).

The composting toilet is not ranked among the most promising methods, though it is one of the top ten when "Familiarity to User" is excluded from consideration. Where user acceptance can be won, they represent a potentially less-expensive way to divert blackwater than microflush toilets. User acceptance may be easiest to win where the composting toilets replace honey bucket systems (Abbot 2004), where they make it possible to save a significant investment on a SAS (numerous examples in Del Porto and Steinfeld 2000), or at facilities that do not have running water.

Biotic sequestration methods were difficult to compare with the others, as the literature search found little cost information. To see whether an additional literature search and interviews were warranted, a sensitivity analysis was performed. Of the biotic systems rated, water hyacinths scored highest when cost information was not included. A score for water hyacinth systems comparable to those in Table 3-2 was then calculated by excluding phosphorus-recycling capability and by rating cost as 5. Even with this optimistic cost rating, water hyacinth systems scored only 3.3, putting them near the bottom of the list.

[2] The scoring system gives the lowest cost score, 1 point, to any system with an added life-cycle cost above $15,000. If the system had been set up to differentiate between systems slightly above and very much above this figure, the microflush toilet may not have ranked so high.

If all criteria other than phosphorus-management capability are excluded from consideration, there are 17 methods that scored 4 or 5, meaning that they have the potential to reduce phosphorus from domestic wastewater by more than 60% (Table 3-4). With this ranking, recently introduced methods like BOF slag and PhosRID compare favorably with packed beds of light-weight aggregate, versions of which have been used for 15 years. The top-ranked methods include Equaris, an expensive, zero-discharge method, and two maintenance-intensive aerobic treatment units.

Almost all of the important data sources used for the most promising 11 methods listed in Table 3-2 were assigned a confidence level of High or Medium, using the scale developed as part of this project's Quality Assurance Project Plan (QAPP) (Etnier *et al.* 2005). For microflush toilets, the data on phosphorus-management capability were assigned a Medium confidence level, but the data on individual brands of toilet were assigned a Low confidence level, as they came from the manufacturers. Two of the manufacturers sell on the order of 10,000 units per year apiece, which indicates some confidence of the market in their products' function. Sales or size of company play no role in the confidence level evaluation of the QAPP.

For the methods most successful at managing phosphorus, listed in Table 3-4, almost all of the most important data sources were assigned a High or Medium confidence level for data on phosphorus-management capability. The data on the Equaris system were assigned a Low confidence level, as they came from the manufacturer. Since the Equaris is a zero-discharge system, it is unlikely to leak much phosphorus—assuming that it works as advertised.

Table 3-4
Phosphorus-Management Methods (excluding biota) Ranked by Phosphorus-Management Capability

Ranking	Method	P Management Score	Weighted Average Score (Without P Recycling Capability)
1	Lightweight aggregates	5	4.6
2	BOF slag in a packed-bed filter	5	4.0
3	Phosrid	5	4.0
4	Sequencing batch reactor	5	3.6
5	Peatland	5	4.2
6	Extended aeration activated sludge	5	3.2
7	Equaris Infinity	5	2.8
8	Limestone as SAS medium	4	5.1
9	Shallow SAS	4	5.0
10	Microflush toilet	4	4.6
11	Compost toilet	4	4.3
12	Timed, pressure dosing	4	3.9
13	Alum injection	4	3.1
14	Comprehensive site assessment	3	5.3
15	Design of long, narrow trenches	3	5.3
16	Tire chips as SAS medium	3	4.5
17	Urine diversion	3	4.3
18	Doping SAS	3	3.7
19	RUCK CFT	3	3.4
20	P-free dishwasher detergent	2	4.9
21	P-free laundry detergent	1	4.9
22	Eliminate garbage disposal	1	4.7
23	Aquatron	1	4.1

Secondary ranking is by weighted average score without phosphorus-recycling capability.

4 RESEARCH AND DEMONSTRATION NEEDS

In this report, a range of phosphorus-management methods has been investigated, from source reduction to the soil absorption system design. Research and demonstration needs for each broad category of methods are examined, and then the top five are identified.

4.1 Research and Demonstration Needs by Category

Of the top ten most promising methods for phosphorus management (Table 3-2), the three source-reduction strategies are sufficiently developed as to require no further research or demonstration. Laundry detergents are already free of phosphorus, so the need is only for monitoring and enforcement to ensure that phosphates do not return to laundry detergent formulations. Dishwasher detergents with little or no phosphorus are readily available, so the policymaker need only decide what combination of incentives, regulations, and monitoring will most effectively ensure that these detergents are used. Similarly, it is well-understood how to plumb houses without garbage disposals and how to compost household organic waste on site or collect it for composting off site.

Most of the methods that scored high on phosphorus management regardless of cost and other factors (Table 3-4) also were among the most promising methods listed in Table 3-2. Of the others, the two aerobic treatment units (extended aeration activated sludge and sequencing batch reactor) plus alum injection generate large amounts of sludge, which makes them an unattractive option for decentralized treatment. The zero-discharge system (Equaris Infinity) is expensive, and its extreme amount of water reuse is unlikely to appeal to many users. The composting toilets are sufficiently mature as a technology that no acute research need is apparent; composting toilets have also recently been the subjects of a demonstration project (Abbot 2004).

Research and/or demonstration needs have been identified for the other most promising methods and others with high phosphorus-management potential. Demonstrations were identified where performance of the science or technology is well-documented in some other way than field experiments in the US.

4.1.1 Source Reduction

No research or demonstration needs are identified for the source-reduction category. Ongoing monitoring of the phosphorus content of detergents is important, however, to ensure that the labels are accurate and all laws are being complied with.

4.1.2 Source Diversion

4.1.2.1 Demonstration Need: Demonstrate Microflush Toilets in Terrestrial Applications

Microflush toilets for marine use are widely sold in the US, but they are relatively rare on land. They have the potential to reduce phosphorus, nitrogen, and organic matter in wastewater from buildings in sensitive environments, for example, right on a lake. They have been tested in such situations in Europe. Would US users accept them? What infrastructure of service providers is necessary to install and service them so they work reliably? Research and/or demonstration of various graywater treatment strategies that could be effective in environmentally-sensitive areas may be connected with this demonstration.

4.1.3 Septic Tank

No research or demonstration needs are identified for the septic tank category.

4.1.4 Post-Septic Tank

4.1.4.1 Demonstration Need: Demonstrate Packed-Bed Filter Media

Basic oxygen furnace (BOF) slag and PhosRID remove large amounts of phosphorus in test centers. How do they perform in real-world situations over time? Lightweight aggregates have some history of use in decentralized wastewater in the US, but a more extensive track record could help build acceptance for them. Demonstrate more packed-bed filters using these media and follow their phosphorus-removal performance over time.

4.1.4.2 Research Need: Identify General Properties of a Sorbent That Make it Useful for Phosphorus Removal

The importance of aluminum, magnesium, calcium, and iron in phosphorus sorption is well understood. What particle size, shape, and surface area are optimal for long-term phosphorus removal? Can waste products like BOF slag or crushed brick perform as well over time as commercial products like lightweight aggregates? What facilitates an ability to reuse the phosphorus in agriculture?

4.1.4.3 Research Need: Continue Developing Nanoparticle Selective Resins

In the laboratory, nanoparticle selective resins show interesting potential for phosphorus removal. They should be developed and used at test centers to understand their potential for use in decentralized wastewater treatment. Questions include:

- How does phosphorus-binding resin perform with municipal strength wastewater?

- Are there qualities of water—biological oxygen demand (BOD), total suspended solids (TSS), and dissolved solids—that optimize their performance and reduce the need for maintenance?
- How can they be configured to optimize their efficiency?
- What are their long-term maintenance and sustainability issues?

4.1.4.4 Research Need: Evaluate the Phosphorus-Recycling Potential of Packed-Bed Filter Media

Phosphorus-recycling potential was identified as a significant criterion for evaluating phosphorus-management methods. However, so little data were found that it was not used in the final ranking of methods. Evaluating the phosphorus recycling potential of different media for packed-bed filters will make possible the choice of phosphorus-management method based on both its protection of water quality and its ability to recycle a valuable and finite resource. Questions to address in the evaluation include:

- How available is the sorbed phosphorus to plants?
- How can the medium be processed to increase the availability of phosphorus?
- To what extent do heavy metals or other properties interfere with land application of the medium?
- How difficult is it to remove and replace the medium? (This last question assumes an optimal filter bed design for each medium.)

4.1.5 Soil Absorption System (SAS)

4.1.5.1 Research Need: Develop a Vulnerability Index for Phosphorus Breakthrough

One of the least expensive phosphorus-removal methods is the one that does not have to be installed because the soil at the site has adequate phosphorus-fixation potential to provide long-term removal. Soil color and texture relative to phosphorus fixation have not been quantified. To exploit the power of comprehensive site assessment in choosing a phosphorus-removal strategy, a site assessment guidance document should be developed that contains a series of soil chemistry tests (metals content, anion exchange capacity, and others) and morphometric tests that could drive the decision on the necessary level of phosphorus-management strategy for the area. For example, if the soils have no anion exchange capacity, no metals, and are extremely coarse (the worst situation), then the resource manager may insist on strategies that would otherwise be unacceptably costly. If the soils are iron or aluminum-rich, fine-textured and there are adequate lateral setbacks, then less-draconian measures may be used. The focus of the research should be on the guidance to evaluate or index the property relative to phosphorus breakthrough vulnerability.

4.1.5.2 Research Need: Document the Long-Term Phosphorus-Removal Potential of Tire Chips and Limestone as SAS Media

Using limestone gravel or tire chips as aggregate in the SAS could capture phosphorus before the effluent enters the soil, so that the development of a phosphorus-sorption front in the soil would be retarded. Replacing SAS media is usually an expensive option; it is important to understand how long non-gravel media remove phosphorus from effluent. Monitoring soil water at sites using these media would help answer this question.

4.1.5.3 Research Need: Quantify the Retarded Rate of Travel for the Phosphorus-Sorption Front by SAS Design and Management

Options to be studied on various soils include shallow placement of the SAS, designing the SAS to be long and narrow, and timed, pressure dosing. The research should include both soil types with various inherent phosphorus-fixation potential and various landscape positions of the SAS (such as, summit, shoulder, backslope, footslope, and toeslope positions), since soil and site conditions interact in influencing the travel time of the phosphorus-sorption front.

4.1.5.4 Research Need: Investigate Methods to Remove and Replace Phosphorus-Sorbing SAS Aggregate When it Becomes Saturated

Both tire chips and limestone have been investigated as aggregates with potential for phosphorus removal, and “doping” the underlying soil has also been investigated. These methods all involve media that, over time, become saturated with phosphorus. Are there ways to construct soil absorption systems so that the media can relatively easily be removed and replaced? What are the relative costs of using the same medium in the SAS versus in a packed-bed filter—which may be easier to access for exchange of the exhausted medium—to achieve the same phosphorus removal?

4.1.5.5 Research Need: Improve the Characterization of Soil Fixation of Phosphorus Species in Septic Tank Effluent by Soil

This basic knowledge could give new insights into potential methods for increasing the long-term sorption capacity of soils.

4.2 Top Five Research and Demonstration Needs

Based on experience and the results of this project, the following research and demonstration needs were identified as top priorities. They are selected to build on some of the most promising methods identified and to represent a range of approaches to phosphorus management. The needs are described in the order in which they appear in Section 4.1, not in order of priority.

4.2.1 Demonstrate Microflush Toilets in Terrestrial Applications

The microflush toilet was ranked in ninth place as a promising method, and microflush toilets are the only one of the most promising methods that is particularly suited to recycling significant amounts of phosphorus to agriculture. Microflush toilets plumbed to a holding tank can substantially reduce phosphorus, nitrogen, and organic loading to the SAS, and may be useful in a wide range of situations with shallow soils and/or close proximity to surface water. A demonstration project could increase interest in using these toilets and document the infrastructure and educational needs to achieve reliable performance and user acceptance.

4.2.2 Identify General Properties of a Sorbent That Make it Useful for Phosphorus Removal

Sorbents can be used both in packed-bed filters and the SAS. They come in a wide variety of shapes, sizes, materials, and costs. If the general physical properties that make a sorbent useful for phosphorus removal are specified, it becomes easier to improve the performance of existing sorbents and to design the “perfect” sorbent.

4.2.3 Demonstrate Packed-Bed Filter Media

A demonstration project could increase interest in using packed-bed filter media that perform well for phosphorus removal and document the maintenance needed to achieve reliable performance.

4.2.4 Continue Developing Nanoparticle Selective Resins

Nanoparticle selective resins, through their capacity for regeneration of phosphorus-sorption potential, may be useful for phosphorus removal. Further research and development is necessary before it is possible to judge how appropriate they are for decentralized wastewater treatment.

4.2.5 Develop a Vulnerability Index for Phosphorus Breakthrough

Comprehensive site assessment is a tool that can be used to discover the need for any sort of phosphorus-removal method beyond the native capacity in the soil. Quantifying the relationship between soil properties and phosphorus absorption capacity could both help site soil absorption systems to maximize phosphorus removal in soil and save money by identifying places where no measures other than SAS siting are needed.

5 REFERENCES

Abassi, S. A. 1987. “Aquatic Plant Based Water Treatment Systems in Asia.” *Aquatic Plants for Water Treatment and Resource Recovery*, edited by K. R. Reddy and F. A. Smith. Magnolia Publishing, Orlando, FL.

Abbot, R. 2004. “Skaneateles Lake Watershed Composting Toilet Project.” *Small Flows Quarterly* 5(2), 32–39.

Adler, P. R., S. T. Summerfelt, D. M. Glenn, and F. Takeda. 1996. “Evaluation of a Wetland System Designed to Meet Stringent Phosphorus Discharge Requirements.” *Water Environ. Research* 68(5), 836–840.

af Petersens, E. 2003. *Småskaliga Avloppsreningsanläggningar - Marknadsöversikt över Prefabricerade Producter för Behandling “i Slutet av Röret.”* VA-Forsk, Svenskt Vatten AB, Stockholm, Sweden.

Al-Shiekh Khalil, W. R., A. Goonetilleke, and P. A. Rigby. 2004. “Use of Undisturbed Soil Columns to Evaluate Soil Capability to Renovate Onsite Sewage Treatment System Effluent.” *Onsite Wastewater Treatment X, Proceedings of the Tenth National Symposium on Individual and Small Community Sewage Systems, at Sacramento, California.* American Society of Agricultural Engineers (ASAE), St. Joseph, MI.

Alaerts, G. J., M. R. Mahbubar, and P. Kelderman. 1996. “Performance Analysis of a Full-Scale Duckweed-Covered Sewage Lagoon.” *Water Research* 30(4), 843–852.

Alhajjar, B. J., J. M. Harkin, and G. Chesters. 1989. "Detergent Formula Effect on Transport of Nutrients to Ground Water From Septic Systems." *Ground Water* 27(2), 209–218.

Ayres Associates. 1998. *Florida Keys Onsite Wastewater Nutrient Reduction Systems Demonstration Project.* Florida Department of Health.

Ayers Associates. 2000. *Florida Keys Onsite Wastewater Nutrient Reduction Systems Demonstration Project: Phase II Addendum.* Florida Department of Health.

Backlund, A., A. Eilersen, I. Larsen, M. Hagelskjær, and G. Jensen. 2003. *Økologisk Håndtering af Urin og Fækalier i Kolonihaveforeninger.* Danish EPA (Miljøstyrelsen), Copenhagen, Denmark.

Berger, W. 2004. “Results in the Use and Practice of Composting Toilets in Multi Story Houses in Bielefeld and Rostock, Germany.” *Ecosan – Closing the Loop Proceedings of the 2nd International Symposium, 7th –11th April 2003, Lübeck, Germany*, edited by C. Werner *et al.* Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany.

Bernard, J. M. and B. A. Solsky. 1977. “Nutrient Cycling in *Carex Lacustris* Wetland.” *Canadian Journal of Botany* 55, 630–638.

Bernard, J. M. 1999. “Seasonal Growth Patterns in Wetland Plants Growing in Landfill Leachate.” *Constructed Wetlands for the Treatment of Landfill Leachates*, edited by G. Mulamottil, E. A. McBean and F. Rovers. CRC Press, LLC, Chelsea, MI.

Bicki, T. J., R. B. Brown, M. E. Collins, R. S. Mansell, and D. F. Rothwell. 1984. "Impact of Onsite Sewage Disposal Systems on Surface and Groundwater Quality." Institute of Food and Agriculture, University of Florida, Gainesville, FL.

Brady, N. C. and R. R. Weil. 2002. *The Nature and Properties of Soils*. 13 ed. Prentice Hall Publishing Company, Upper Sadler River, NJ.

Brandes, M. 1977. “Effective Phosphorus Removal by Adding Alum to Septic Tank.” *Journal Water Pollution Control Federation* 49(11), 2285–2296.

Breen, P. F. 1990. “A Mass Balance Method for Assessing the Potential of Artificial Wetlands for Wastewater Treatment.” *Water Research* 24(6), 689–697.

Brix, H. 1994. “Use of Constructed Wetlands in Water Pollution Control: Historical Development, Present Status, and Future Perspectives.” *Water Science and Technology* 30(8), 209–223.

Brooks, J. L., C. A. Rock, and R. A. Struchtemeyer. 1984. “Use of Peat for Onsite Wastewater Treatment: II. Field Studies.” *Journal of Environmental Quality* 13(4), 524–530.

Brown, S. 1981. “A Comparison of the Structure, Primary Productivity and Transpiration of Cypress Ecosystems in Florida.” *Ecological Monographs.* 51, 403–427.

Bruce, R. 2004. *A New Image for the Water Hyacinth* [Web page]. Stennis Space Center Technology Development and Transfer Office Undated. [Cited July 6, 2004]. Available from http://technology.ssc.nasa.gov/suc_stennis_water.html

Buol, S. W. and F. D. Hole. 1959. “Some Characteristics of Clay Skins on Peds in the B Horizon of a Gray-Brown Podzolic Soil.” *Proceedings - Soil Science Society of America.* 23, 239–241.

Buol, S. W., F. D. Hole, and R. J. McCracken. 1980. *Soil Genesis and Classification*. 2nd ed. Iowa State University Press, Ames, IA.

Bush, A. F., J. D. Isherwood, and S. Rodgi. 1963. "Dissolved Solids Removal From Wastewater by Algae." *Transactions of the American Society of Civil Engineers* 128, 84–102.

Campbell, C. S. and M. H. Ogden. 1999. *Constructed Wetlands in the Sustainable Landscape*. Wiley and Sons, New York, NY.

Cantor, L. W. and R. C. Knox. 1986. *Septic Tank Effects on Groundwater Quality*. Lewis Publishers, Inc., Chelsea, MI.

Carpenter, S. R., S. W. Chrisholm, C. J. Krebs, D. W. Schindler, and R. F. Wright. 1995. "Ecosystem Experiments." *Science* 269, 324–327.

Cheung, K. C., T. H. Venkitchalam, and W. D. Scott. 1994. "Selecting Soil Amendment Materials for Removal of Phosphorus." *Water Science and Technology* 30, 247–256.

Clark, S. 2000. "Development of a Biologically-Integrated Food-Waste Composting System" [cited August 5, 2004]. Available from http://www.ofrf.org/publications/Grant%20reports/99.40.11.Clark.Spr99.IB10.pdf

Cloris, M. and H. Aruajo. 1987. "Use of Water Hyacinth in Tertiary Treatment of Domestic Sewage." *Water Science and Technology* 19(10), 11–17.

Coleman, J., K. Hench, K. Garbutt, A. Sexstone, G. Bissonnette, and J. Skousen. 2001. "Treatment of Domestic Wastewater by Three Plant Species in Constructed Wetlands." *Water Air and Soil Pollution* 128(3-4), 283–295.

Cooke, G. D., E. B. Welch, S. A. Peterson, and P. R. Newroth. 1993. *Restoration and Management of Lakes and Reservoirs*. Lewis Publishers, New York, NY.

Correll, D. L. 1998. "The Role of Phosphorus in the Eutrophication of Receiving Waters—A Review." *Journal of Environmental Quality* 27, 261–266.

Couillard, D. 1994. "The Use of Peat in Wastewater Treatment." *Water Research* 28(6), 1261–1274.

Craggs, R. J. 2001. "Wastewater Treatment by Algal Turf Scrubbing." *Water Science and Technology* 44(11-12), 427–433.

Crites, R. and G. Tchobanoglous. 1998. *Small and Decentralized Wastewater Management Systems*. WCB/McGraw-Hill, Boston, MA.

Crites, R. F., S. C. Reed, and R. K. Bastian. 2000. *Land Treatment Systems for Municipal and Industrial Wastes*. McGraw-Hill, New York, NY.

Cross, P. and M. Strauss. 1986. *Health Aspects of Nightsoil and Sludge Use In Agriculture and Aquaculture.* International Reference Centre for Waste Disposal, Duebendorf, Switzerland.

Culley Jr., D. D. and A. E. Epps. 1973. "Use of Duckweed for Waste Treatment and Animal Feed." *Journal of the Water Pollution Control Federation* 45(2), 337–347.

Culley Jr., D. D. and R. W. Myers. 1980. *Effect of Harvest Rate on Duckweed Yield and Nutrient Extraction in Dairy Waste Lagoon.* (Polycopy). Baton Rouge, LA.

Cuyk, S. V., R. Siegrist, A. Logan, S. Masson, E. Fischer, and L. Figueros. 2001. "Hydraulic and Purification Behaviors and Their Interactions During Wastewater Treatment in Soil Infiltration Systems." *Water Research* 35, 953–964.

Davis, M.A. 1999. *Phosphorus Removal From Recirculating Sand Filter Effluent by Lime Addition.* Masters of Science, Civil Engineering, University of Arkansas, Fayetteville, AR.

DeBusk, T. A. 1984. *Nutrient Dynamics in a Cypress Stand Receiving Municipal Wastewater Effluent.* University of Florida, Gainesville, FL.

DeBusk, T. A. 2001. "The Use of Macrophyte-Based Systems for Phosphorus Removal: An Overview of 25 Years of Research and Operational Results in Florida." *Water Air and Soil Pollution* 44(11-12), 39–46.

DeBusk, T. A. and K. R. Reddy. 1989. "Wastewater Nutrient Removal in Florida Using Aquatic Macrophytes." *Proceedings, Biological Nitrogen and Phosphorus Removal: the Florida Experience ll.* University of Florida TREECO Center, Gainesville, FL.

Deeny, K., H. Hahn, D. Leonhard, and J. Heidman. 1991. "Autoheated Thermophilic Aerobic Digestion." *Water Environment and Technology* 3(10), 65–72.

Del Porto, D. and C. Steinfeld. 2000. *The Composting Toilet System Book*. Version 1.2. Center for Ecological Pollution Prevention, Concord, MA.

Dierberg, F. E. 1980. T*he Effects of Secondary Sewage Effluent on the Water Quality, Nutrient Cycles and Mass Balances, and Accumulation of Soil Organic Matter in Cypress Domes.* University of Florida, Gainesville, FL.

Dodds, W. K. 2003. "The Role of Periphyton in Phosphorus Retention in Shallow Freshwater Aquatic Systems." *Journal of Phycology* 39(5), 840–849.

Downing, T. 2002. *Nitrogen, Phosphorus, and Potassium Uptake in Perennial Grasses Fertilized with Dairy Manure.* Oregon State University Extension Service, Tillamook, OR.

Earthmaker NZ. 2002. Earthmaker Experts [Manufacturer's web page]. Earthmaker Compost Analysis [cited August 4, 2004]. Available at http://www.earthmaker.co.nz/experts.htm

Edwards, P. 1980. *Food Potential of Aquatic Macrophytes.* ICLARM Studies and Reviews.

Etnier, C. and B. Guterstam, eds. 1997. *Ecological Engineering for Wastewater Treatment*. Second ed. CRC Lewis Publishers, Boca Raton, FL.

Etnier, C., G. Norén, and R. Bogdanowicz, eds. 1997. *Ecotechnology for Wastewater Treatment: Functioning Facilities in the Baltic Sea Region*. Coalition Clean Baltic, Gdańsk, Poland.

Etnier, C. and K. Refsgaard. 1998. *Costs for Treatment of Blackwater With Source Separation, Liquid Composting, and Spreading in Agriculture.* (In Norwegian). Norwegian Agricultural Economics Research Institute, Oslo, Norway.

Flaherty, L. J. 2002. *Hybrid Poplars in Dryland Riparian Agricultural Buffers in Eastern Washington: Performance and Phosphorus Removal.* Ph. D. Dissertation, Program in Environmental Science and Regional Planning, Department of Natural Resource Sciences, Washington State University.

Fox, R. L. and E. J. Kamprath. 1970. "Phosphate Sorption Isotherms for Evaluating the Phosphate Requirements of Soils." *Proceedings—Soil Science Society of America* 34, 902–907.

Geary, P. M. 2004. "Effluent Tracing and the Transport of Contaminants From a Domestic Septic System." *1st International Conference on Onsite Wastewater Treatment and Recycling. 11–13 Feb 2004, at Freemantle, Western Australia.*

Geary, P. M. and J. A. Moore. 1999. "Suitability of a Treatment Wetland for Dairy Wastewaters." *Water Science and Technology* 40(3), 179–185.

Gold, A. J. and J. T. Sims. 2000. "Research Needs in Decentralized Wastewater Treatment and Management: A Risk-Based Approach to Nutrient Contamination." *National Research Needs Conference: Risk-Based Decision Making for Onsite Wastewater Treatment; May 19–20, 2000, March 15, 2001, at St. Louis, MO.* Available at http://www.ndwrcdp.org/userfiles/RESEARCH_NEEDS_PROCEEDINGS_CD.PDF

Goodtech Biovac AS. 2004. *Produkter* [Manufacturer's web page]. Goodtech Biovac AS 2004 [cited June 25, 2004]. Available from http://www.biovac.com/produkter/minirenseanlegg/index.htm

Gregersen, P. and H. Brix. 2001. "Zero Discharge of Nutrients and Water in a Willow Dominated Constructed Wetland." *Water Science and Technology* 44(11), 407–412.

Grimes, B. H., S. Steinbeck, and A. Amoozegar. 2003. "Analysis of Tire Chips as a Substitute for Stone Aggregate in Nitrification Trenches of Onsite Septic Systems: Status and Notes on the Comparative Macrobiology of Tire Chip Versus Stone Aggregate Trenches." *Small Flows Quarterly* 4(4), 18–23.

Gulbrandsen, A. 1999. "A Water Saving Vacuum System for Transport of Blackwater and Onsite Treatment of Greywater in a Constructed Wetland." (In Norwegian). M.Sc., Dept. of Engineering, Agricultural University of Norway, Ås, Norway.

Guo, L. B., R. E. H. Sims, and D. J. Horne. 2002. “Biomass Production and Nutrient Cycling in Eucalyptus Short Rotation Energy Forests in New Zealand. I: Biomass and Nutrient Accumulation.” *Bioresource Technology* 85(3), 273–283.

Hammouda, O., A. Gaber, and M. S. Abdel-Hameed. 1995. “Assessment of the Effectiveness of Treatment of Wastewater-Contaminated Aquatic Systems with *Lemna gibba*.” *Enzyme and Microbial Technology* 17(4), 317–323.

Han, J. S. 2002. *New York City Watershed Study.* USDA Forest Service, Forest Products Laboratory, Madison, WI.

Harrison, E. Z., M. B. McBride, and D. R. Bouldin. 1999. “Land Application of Sewage Sludges: An Appraisal of the US Regulations.” *International Journal of Environment and Pollution* 11(1), 1–39.

Hazeltine, T. R. 1951. “Addition of Garbage to Sewage.” *Water And Sewage Works*. 151–154. Annual Compilation, 1951.

Hecky, R. E. and P. Kilham. 1988. “Nutrient Limitation of Phytoplankton in Freshwater and Marine Environments: A Review of Recent Evidence on the Effects of Enrichment.” *Limnology and Oceanography* 33, 796–822.

Hellström, D., L. Jonsson, and M. Sjöström. 2003. *Bra små avlopp: Slutrapport - Utvärdering av 15 Enskilda Avloppsanläggningar.* Stockholm Water, Stockholm, Sweden.

Hemens, J. and M. H. Mason. 1968. “Sewage Nutrient Removal by a Shallow Algal Stream.” *Water Research* 2(2), 77–87.

Hoffmann, J. P. 1998. “Wastewater Treatment With Suspended and Nonsuspended Algae.” *Journal of Phycology* 34(5), 757–763.

Höglund, C. 2001. “Evaluation of Microbial Health Risks Associated With the Reuse of Source-Separated Human Urine.” Ph.D. Dissertation, Dept. of Biotechnology, Applied Microbiology, Royal Institute of Technology, Stockholm, Sweden.

Holden, S., M. Stolt, G. Loomis, and A. Gold. 2004. “Nitrogen and Phosphorus Treatment and Leaching From Shallow Narrow Drainfields.” *Proceedings of NOWRA 2004 Annual Conference & Exposition, November 7-10, 2004, at Albuquerque, New Mexico USA.* National Onsite Wastewater Recycling Association, Edgewater, MD.

Hoover, M. T. 1997. *A Framework for Site Evaluation, Design, and Engineering of Onsite Technologies Within a Management Context.* Marine Studies Consortium, Waqoit Bay National Estuarine Research Reserve, and the ad hoc Task Force for Decentralized Wastewater Management, Chestnut Hill, MA.

Horne, A. J. and C. R. Goldman. 1994. *Limnology*. 2nd ed. McGraw-Hill, New York, NY.

Jackson, D. F. and B. B. Jackson. 1972. “Removal of Phosphates in Wastewater by the Periphyton Communities of Rotating Disks.” *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* 18, 881–890.

Jenssen, P. D., T. Mæhlum, T. Krogstad, and L. Vråle. 2002. “High Performance Constructed Wetlands for Cold Climates.” *8th International Conference on Wetlands for Water Pollution Control.* September 16–19, 2002, Arusha, Tanzania.

Jenssen, P. D. and L. Vråle. 2004. “Greywater Treatment in Combined Biofilter/Constructed Wetlands in Cold Climate.” *Ecosan – Closing the Loop: Proceedings of the 2nd International Symposium, 7th –11th April 2003, Lübeck, Germany*, edited by C. Werner *et al.* Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany.

Johansson, M. 2000. *Urinsortering - en Del i Kretsloppet.* Byggforskningsrådet, Stockholm, Sweden.

Jones, E. R. and S. D. Hubbard. 1986. “Maryland's Phosphate Detergent Ban - History and Early Results.” *Journal of the Water Pollution Control Federation* 8(8), 816–822.

Jönsson, H., B. Vinnerås, C. Höglund, T. Stenström, G. Dalhammar, and H. Kirchmann. 2000. *Källsorterad Humanurin i Kretslopp.* VAV, Stockholm, Sweden.

Kadlec, R., H. 1999. “Constructed Wetlands for Treating Landfill Leachate.” *Constructed Wetlands for the Treatment of Landfill Leachates,* edited by G. Mulamoottil, E. A. McBean, and F. Rovers. CRC/Lewis, Boca Raton, FL.

Kimochi, Y., H. N. Kong, M. Mizuochi, R. Inamori, Y. Inamori, Y. Shimizu, and R. Sudo. 2004. “Advanced Nitrogen and Phosphorus Removal Using the Two-Stage Anaerobic Filter and Soil Trench Wastewater Treatment System.” *1st International Conference on Onsite Wastewater Treatment and Recycling, 11-13 Feb 2004, at Freemantle, Western Australia.*

King, F. H. 1911. *Farmers of Forty Centuries; or, Permanent Agriculture in China, Korea, and Japan*. Mrs. F. H. King, Madison, WI.

Koivula, N., K. Hänninen, and O. Tolvanen. 2000. “Windrow Composting of Source Separated Kitchen Biowastes in Finland.” *Waste Management and Research* 18(2), 160–173.

Korner, S. and J. E. Vermaat. 1998. “The Influence of *Lemna gibba L*., Bacteria, and Algae for the Nitrogen and Phosphorus Removal in Duckweed Covered Domestic Wastewater.” *Water Research* 32, 3651–3661.

Korner, S., J. E. Vermaat, and S. Veenstra. 2003. “The Capacity of Duckweed to Treat Wastewater: Ecological Considerations for a Sound Design.” *Journal of Environmental Quality* 32(5), 1583–1590.

Kvet, J. 1973. "Mineral Nutrients in Shoots of Reed *Phragmites Communis Trin*." *Polskie Archiwum Hydrobiologia* 20, 137–147.

Laak, R. 1988. "Passive Removal of Nitrogen and Phosphorus Using an Alternative Onsite Wastewater System." *Alternative Waste Treatment Systems*, edited by R. Bhamidimarri. Elsevier Applied Science, London, England.

Laquali, G., J. Brisson, L. Dumont, and G.Vincent. 1998. "Nitrogen and Phosphorus Removal in a Subsurface-Flow Reed Bed." *Water Qual. Res. J. Canada* 33(20), 219–329.

Leng, R. A. 1999. *Duckweed, a Tiny Aquatic Plant With Enormous Potential for Agricultural and Environment.* United Nations Food and Agricultural Organization.

Levine, S. N. and D. W. Schindler. 1989. "Phosphorus, Nitrogen, and Carbon Dynamics of Lake 303 During Recovery From Eutrophication." *Canadian Journal of Fisheries and Aquatic Sciences.* 46, 2–10.

Litke, D. W. 1999. *Review of Phosphorus Control Measures in the United States and Their Effects on Water Quality.* US Geological Survey, Denver, CO.

Liu, J., C. Qiu, B. Xiao, and Z. Cheng. 2000. "The Role of Plants in Channel-Dyke and Field Irrigation Systems for Domestic Wastewater Treatment in an Integrated Eco-Engineering System." *Ecological Engineering* 15(2), 235–241.

Lombardo P., W. Robertson, A. Mehrotra, C. Ptacek and D. Blowes. Submitted. *Phosphorus Geochemistry in Septic Tanks, Soil Absorption Systems, and Groundwater.* Project No. WU-HT-03-21. Prepared for the National Decentralized Water Resources Capacity Development Project, Washington University, St. Louis, MO, by Lombardo Associates, Inc., Newton, MA.

Lombardo, P. 2003. "Passive Nitrogen and Phosphorus Removal Systems: Treatment Performance." *Onsite Wastewater Treatment X, Proceedings of the Tenth National Symposium on Individual and Small Community Sewage Systems, at Sacramento, California.* ASAE, St. Joseph, MI.

Ludwig, A. 2000. *Create an Oasis With Greywater: Your Complete Guide to Choosing, Building, and Using Greywater Systems,* 4th ed., Oasis Design, Santa Barbara, CA.

Manahan, S. E. 1994. *Environmental Chemistry*. 6th ed. CRC Press, Inc., Boca Raton, FL.

Mander, Ü., V. Kuusemets, M. Oovel, R. Ihme, P. Sevola, and A. Pieterse. 2000. "Experimentally Constructed Wetlands for Wastewater Treatment in Estonia." *Journal of Environmental Science and Health* A35(8), 1389–1401.

Matsui, S. 1997. "Nightsoil Collection and Treatment in Japan." *Ecological Alternatives in Sanitation*, edited by J.-O. Drangert, J. Bew and U. Windblad. SIDA, Swedish International Development Cooperation Agency, Stockholm, Sweden.

Mayer, P. W., W. B. DeOreo, E. M. Opitz, J. C. Kiefer, W. Y. Davis, B. Dziegielewski, and J. O. Nelson. 1999. *Residential End Uses of Water*. American Water Works Association Research Foundation, Denver, CO.

McBride, M. B. 1994. *Environmental Chemistry of Soils*. Oxford University Press, New York, NY.

McKenzie, C. M. 2003. "Tire Chips a Growing Trend as Aggregate in Soil Absorption Systems." *Small Flows Quarterly* 4(4), 14–17.

Metcalf & Eddy. 1991. *Wastewater Engineering Treatment, Disposal, Reuse*. 3rd ed. McGraw-Hill, Inc., New York, NY.

Meuleman, A. F. M., J. P. Beekman, and J. T. A. Verhoeven. 2002. "Nutrient Retention and Nutrient-Use Efficiency in *Phragmites Australis* Stands After Wastewater Application." *Wetlands* 22(4), 712–721.

Miles, R. J. 1998. "Utilizing Soil Morphology and Landscapes Properties for Siting, Sizing, and Designing Onsite Wastewater Treatment and Disposal Systems." *6th Annual Nonpoint Source Pollution Management Workshop, March 23–25, 1998.*

Miles, R. J. and L. T. West. 2001. "Soil-Based Assessment of Site Suitability for Onsite Wastewater Treatment Systems: A Comparison of the Georgia and Missouri systems." *Proceedings of the Ninth National Symposium on Individual and Small Community Sewage Systems.* ASAE, St. Joseph, MI.

Minnesanteckningar. 2002. *Minnesanteckningar förda vid Referensseminarium för Urban Waters Modellstad "Urbana Enklaven."* Skarpnäck, Sweden.

Mitsch, W. J., C. L. Dorge, and J. R. Wiemboff. 1979. "Ecosystem Dynamics and a Phosphorus Budget of an Alluvial Cypress Swamp in Southern Illinois." *Ecology (Washington, D. C.)* 60, 1116–11124.

Monnett, G. T., R. B. Reneau, Jr., and C. Hagedorn. 1996. "Evaluation of Spray Irrigation for Onsite Wastewater Treatment and Disposal on Marginal Soils." *Water Environment Research* 68, 11–18.

Motavalli, P. P. and R. J. Miles. 2002. "Soil Phosphorus Fractions After 111 Years of Animal Manure and Fertilizer Applications." *Biology and Fertility of Soils* (36), 35–42.

Mulamoottil, G., E. McBean, and F. Rovers, eds. 1999. *Constructed Wetlands for the Treatment of Landfill Leachates.* CRC, Boca Raton, FL.

NASA/NSTL. 1980. *Alternative Wastewater Treatment: Aquatic and Land Systems*, *Water Research Capsule Report*, US GPO, Washington, D. C.

Nelson, V. I. 2003. *Soft Path Integrated Water Resource Management: Training, Research, and Development Needs.* Prepared for the National Decentralized Water Resources Capacity Development Project, Washington University, St. Louis, MO, by the Coalition for Alternative Wastewater Treatment, Gloucester, MA.

Nemcova, M., D. Cadelli, and M. Radoux. 1999. “Role of Terrestrial Ecosystems Planted With Ligneous Species in MHEA Systems Receiving Urban Wastewaters.” *Water Science and Technology* 40(30), 187–193.

Nessel, J. K. and S. E. Bayley. 1984. “Distribution and Dynamics of Organic Matter and Phosphorus in Sewage Enriched Cypress Swamp.” *Cypress Swamps*, edited by K. C. Ewel and H. T. Odem. Univ. of Florida Press, Gainesville, FL.

Nhapi, I., J. Dalu, J. Ndamba, M. A. Siebel, and H. J. Gijzen. 2003. “An Evaluation of Duckweed-Based Pond Systems as an Alternative Option for Decentralised Treatment and Reuse of Wastewater in Zimbabwe.” *Water Science and Technology* 48(2), 323–330.

Nichols, D. S. and D. H. Boelter. 1982. “Treatment of Secondary Sewage Effluent With a Peat-Sand Filter Bed.” *Journal of Environmental Quality* 11(1), 86–92.

Nichols, D. S. 1983. “Capacity of Natural Wetlands to Remove Nutrients From Wastewater.” *Journal Water Pollution Control Federation* 55(5), 495–504.

Norin, E., C. Gruvberger, and P. O. Nilsson. 2000. *Hantering av Svartvatten Från Tegelvikens Skola – Kretsloppssystem med Våtkompostering.* VA-FORSK, Stockholm, Sweden.

Nungesser, M. K. and M. J. Chimney. 2001. “Evaluation of Phosphorus Retention in a South Florida Treatment Wetland.” *Water Science and Technology* 44(11–12), 109–115.

Oakley, S. 2003. *Onsite Nitrogen Removal: Consortium of Institutes for Decentralized Wastewater Treatment.*

Obek, E. and H. Hasar. 2002. “Role of Duckweed (*Lemna minor L.*) Harvesting in Biological Phosphate Removal From Secondary Treatment Effluents.” *Fresenius Environmental Bulletin* 11(1), 27–29.

Organization for the Assabet River. 2003. *Friend or phosphate?* [Website]. Organization for the Assabet River 2003 [cited September 2003]. Available from http://www.assabetriver.org/nutrient/detergents.html

Oron, G., L. R. Wildschut, and D. Parath. 1984. “Wastewater Recycling by Duckweed for Protein Production and Effluent Renovation.” *Water Science and Technology* 17(4/5), 803–817.

Otterpohl, R., U. Braun, and M. Oldenburg. 2002. "Innovative Technologies for Decentralised Wastewater Management in Urban and Peri-Urban Areas." *IWA Fifth Specialized Conference on Small Water and Wastewater Treatment Systems,* Istanbul, Turkey.

Pace, M. L. and E. Funke. 1991. "Regulation of Planktonic Microbial Communities by Nutrients and Herbivores." *Ecology* 72, 904–914.

Palmstrom, N. S., R. E. Carlson, and G. D. Cooke. 1988. "Potential Links Between Eutrophication and the Formation of Carcinogens in Drinking Water." *Lake and Reservoir Management* 4, 1–15.

Panesar, A. and J. Lange. 2004. "Innovative Sanitation Concept Shows Way Towards Sustainable Urban Development: Experiences from the Model Project "Wohnen & Arbeiten" in Freiburg, Germany." E*cosan – Closing the Loop: Proceedings of the 2nd International Symposium, 7th –11th April 2003, Lübeck, Germany*, Edited by C. Werner *et al.* Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany.

Patterson, J. C. and J. R. Short. 1985. *Project Summary: Liquid Waste Composting,* Edited by U. E. W. E. R. Laboratory, US EPA.

Patterson, R. A. 2004. "Effective Treatment of Domestic Effluent With a Peat Biofilter - A Case Study at Tingha." *Onsite Wastewater Treatment X, Proceedings of the Tenth National Symposium on Individual and Small Community Sewage Systems, at Sacramento, California.* ASAE, St. Joseph, MI.

Pell, M. and F. Nyberg. 1989. "Infiltration of Wastewater in a Newly Started Pilot Sand-Filter System: Reduction of Organic Matter and Phosphorus." *Journal of Environmental Quality* 18, 451–457.

Petruzzelli, D., L. De Florio, A. Dell'Erba, L. Liberti, M. Notarnicola, and A. K. Sengupta. 2003. "A New Phosphate-Selective Sorbent for the Rem Nut Process. Laboratory Investigations and Field Experience at a Medium Size Wastewater Treatment Plant." *Water Science and Technology* 48(1), 179–184.

Peverly, J., W. E. Sanford, T. S. Steenhuis, and J. Surface. 1993. *Constructed Wetlands for Municipal Solid Waste Landfill Leachate Treatment.* New York State Energy Research and Development Authority.

Philippi, L. S., R. H. R. da Costa, and P. H. Sezerino. 1999. "Domestic Effluent Treatment Through Integrated System of Septic Tank and Root Zone." *Water Science and Technology* 40(3), 125–131.

Phosphates: A Sustainable Future in Recycling. 1998. CEFIC-CEEP (European Chemical Industry Council-Centre Europeen d'Etudes des Polyphosphates), Bruxelles, Belgium.

Proctor, D. M., K. A. Fehling, E. C. Shay, J. L. Wittenborn, J. J. Green, C. Avent, R. D. Bigham, M. Connolly, B. Lee, T. O. Shepker, and M. A. Zak. 2000. "Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace Steel Industry Slags." *Environmental Science and Technology* 34(8), 1576–1582.

Rasmussen, G., P. D. Jenssen, and L. Westlie. 1996. "Graywater Treatment Options." *Recycling the Resource: Proceedings of the Second International Conference on Ecological Engineering for Wastewater Treatment, Waedenswil, Switzerland, Sept. 18–22, 1995.* Edited by J. Staudenmann, A. Schönborn, and C. Etnier, Transtec Publications, Zuerich-Uetikon, Switzerland.

Recovery of Phosphates for Recycling. 1998. CEFIC-CEEP, Bruxelles, Belgium.

Reddy, G. B., P. G. Hunt, R. Phillips, and A. Grubbs. 2001. "Treatment of Swine Wastewater in Marsh-Pond-Marsh Constructed Wetlands." *Water Science and Technology* 44(11–12), 545–550.

Reddy, K. R. and T. A. DeBusk. 1985. "Nutrient Removal Potential of Selected Aquatic Macrophytes." *Journal of Environmental Quality* 14, 459–462.

Reddy, K. R. and T. A. DeBusk. 1987. "State of the Art Utilization of Aquatic Plants in Water Pollution Control." *Water Science and Technology* 19(10), 61–79.

Reed, S. C., R. Crites, and E. J. Middlebrooks. 1995. *Natural Systems for Waste Management and Treatment*. 2nd ed. McGraw-Hill. New York, NY.

Refsgaard, K. and C. Etnier. 1998. *Natural Systems Technology for Wastewater Treatment in Rural Areas: Economic and Environmental Evaluation for Rural Municipalities, Households, and Farms.* (In Norwegian). Norwegian Agricultural Economics Research Institute, Oslo, Norway.

Reneau, Jr., R. B., C. Hagedorn, and M. J. Degen. 1989. "Fate and Transport of Biological and Inorganic Contaminants From Onsite Disposal of Domestic Wastewater." *Journal of Environmental Quality* 18(135–144).

Reneau, Jr., R. B. and D. E. Pettry. 1975. "Phosphorus Distribution From Septic Tank Effluent in Coastal Plain Soils." *Journal of Environmental Quality* 5, 34–38.

Reneau, Jr., R. B. 1979. "Changes in Concentrations of Selected Chemical Pollutants in Wet, Tile-Drained Soil Systems as Influenced by Disposal of Septic Tank Effluent." *Journal of Environmental Quality* 8, 189–196.

Richter, A. Y. and R. W. Weaver. 2004. "Phosphorus Reduction in Effluent From Subsurface-Flow Constructed Wetlands Filled With Tire Chips." *Onsite Wastewater Treatment X, Proceedings of the Tenth National Symposium on Individual and Small Community Sewage Systems, at Sacramento, California.* ASAE, St. Joseph, MI.

Ridderstolpe, P. 1999. *Wastewater Treatment in a Small Village: Options for Upgrading.* Water Revival Systems Ekoteknik AB, Uppsala, Sweden.

Robertson, W. D. 2000. "Treatment of Wastewater Phosphate by Reductive Dissolution of Iron." *Journal of Environmental Quality* 29, 1678–1685.

Robertson, W. D. and J. Harman. 1999. "Phosphorus Plume Persistence at Two Decommissioned Septic System Sites." *Ground Water* 37, 228–236.

Robertson, W. D., S. L. Schiff, and C. J. Ptacek. 1998. "Review of Phosphate Mobility and Persistence in 10 Septic System Plumes." *Ground Water* 36, 100–110.

Rohrer, T. 2003. *Detergent Phosphorus and the Soap Police* [Website] 1999 [cited September 2003]. Available from http:www.great-lakes.net/lists/enviro-mich/1999-10/msg00087.html

Ryding, S. O. and W. Rast, eds. 1989. "The Control of Eutrophication of Lakes and Reservoirs." Vol. 1, *Man and the Biosphere Series*. The Parthenon Publishing Group, Park Ridge, NJ.

Sanchez, P. A. and G. Uehara. 1980. "Management Considerations for Acid Soils With High Phosphorus Fixation Capacity." *The Role of Phosphorus in Agriculture*, Edited by F. E. Khasawneh, E. C. Sample and E. J. Kamprath. American Society of Agronomy, Madison, WI.

Sawhney, B. L. and D. E. Hill. 1975. "Phosphate Sorption Characteristics of Soils Treated With Domestic Wastewater." *Journal of Environmental Quality* (4), 342–346.

Schaafsma, J. A., A. H. Baldwin, and C. A. Streb. 2000. "An Evaluation of a Constructed Wetland to Treat Wastewater From a Dairy Farm in Maryland, USA." *Ecological Engineering* 14(2), 199–206.

Schindler, D. W. 1977. "Evolution of Phosphorus Limitation in Lakes." *Science* (195), 260–262.

Schlesinger, W. H. 1978. "Community Structure Dynamics and Nutrient Cycling in the Okefenokee Cypress Swamp Forest." *Ecological Monographs* 48, 43–75.

Schönborn, A., B. Züst, and E. Underwood. 1996. "Long Term Performance of the Sand Plant Filter Schattweid." *Fifth International Conference on Wetland Systems for Water Pollution Control, in Switzerland.*

Sedlak, R. I. 1991. *Phosphorus and Nitrogen Removal From Municipal Wastewater: Principles and Practice*. Lewis Publishers, Boca Raton, FL.

Sharpley, A. N., S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel, and K. R. Reddy. 1994. "Managing Agricultural Phosphorus for Protection of Surface Water: Issues and Options." *Journal of Environmental Quality* 23, 437–451.

Siegrist, R. L., J. McCray, L. Weintraub, C. Chen, J. Bagdol, P. Lemonds, S. Van Cuyk, K. Lowe, R. Goldstein, and J. Rada. 2005. *Quantifying Site-Scale Processes and Watershed-Scale Cumulative Effects of Decentralized Wastewater Systems.* Project No. WU-HT-02-27. Prepared for the National Decentralized Water Resources Capacity Development Project, Washington University, St. Louis, MO, by the Colorado School of Mines, Golden, CO.

Sievers, D. M. and R. J. Miles. 1995. *Design and Construction of Onsite Systems.* Special Report 477: Agricultural Experiment Station, College of Agriculture, Food and Natural Resources, University of Missouri—Columbia.

Skjelhaugen, O. J. 1999. "Closed System for Local Reuse of Blackwater and Food Waste, Integrated with Agriculture."*Water Science and Technology* 39(5), 161–168.

Smyth, D. J. A., D. W. Blowes, C. J. Ptacek, S. Foss, E. Bernstene, and P. Lombardo. Undated. *Removal of Phosphate and Waterborne Pathogens From Wastewater Effluent Using Permeable Reactive Materials.* Lombardo Associates, Concord, MA.

Son, Y. and S. T. Gower. 1992. "Nitrogen and Phosphorus Distribution for Five Plantation Species in Southwestern Wisconsin." *Forest Ecology and Management* 53, 175–193.

Soto, F., M. Garcia, E. de Luis, and E. Becares. 1999. "Role of *Scirpus Lacustris* in Bacterial and Nutrient Removal From Wastewater." *Water Science and Technology* 40(3), 241–247.

Staudenmann, J., A. Schönborn, and C. Etnier, eds. 1996. *Recycling the Resource: Ecological Engineering for Wastewater Treatment*. Vol. 5-6, *Environmental Research Forum*. Transtec Publications, Zuerich-Uetikon, Switzerland.

Stone Environmental, Inc. 2004. *Quality Assurance Project Plan for Micro-Scale Evaluation of Phosphorus Management Part II: Alternative Wastewater Systems Evaluation.* Prepared for the National Decentralized Water Resources Capacity Development Project, St. Louis, MO, by Stone Environmental, Inc., Montpelier, VT.

Stucky, M. 2003. *State to Ban Phosphorus in Dishwasher Soap?* [Website]. Great Lakes Radio Commission 2003 [cited September 2003]. Available from http://www.glrc.org/transcript.php3?story_id=1896

Swedish EPA. 1995. Vad Innehåller Avlopp Från Hushåll: Näring och Metaller i Urin och Fekalier samt i Disk-, Tvätt-, Bad-, Och Duschvatten. Swedish EPA (Naturvårdsverket), Stockholm, Sweden.

Swedish EPA. 2002. Robusta, Uthålliga Små Avloppssystem - En Kunsksapssammanställning. Naturvårdsverket, Stockholm, Sweden.

Tanner, C. C. 1994. "Treatment of Agricultural Wastewater and Growth of Schoenoplectus Validus in Agricultural Wastewater." *Aquatic Botany* 47, 131–153.

Tanner, C. C., J. P. S. Sukias, and M. P. Upsdell. 1999. "Substratum Phosphorus Accumulation During Maturation of Gravel-Bed Constructed Wetlands." *Water Science and Technology* 40 (3), 147–154.

Tilman, D., S. S. Kilham, and P. Kilham. 1982. "Phytoplankton Community Ecology: The Role of Limiting Nutrients." *Annual Review of Ecological Systems* 13, 349–372.

Tip of the Mitt Watershed Council. 2000. *Focus Article: Phosphorus Ban and Detergents* [Website]. Tip of the Mitt Watershed Council 2000 [cited September 2003]. Available from http://www.watershedcouncil.org/

Tisdale, S. L., W. L. Nelson, J. D. Beaton, and J. L. Havlin. 1993. *Soil Fertility and Fertilizers*. 5th ed. Macmillan Publishing Co., New York, NY.

Todd, J. 1986. "Architecture and Biology: A Necessary Synthesis." *Sustainable Communities*, edited by S. V. d. Ryn and P. Calthorpe. Sierra Club Books, San Francisco, CA.

Todd, J. 2000. "Towards a Post Engineering Perspective on Wastewater Treatment." *Annals of Earth* 18(1).

Todd, J. and B. Josephson. 1996. "The Design of Living Machines for Wastewater Treatment." *Ecological Engineering* 6, 109–136.

Todd, J., E. Brown, and E. Wells. 2000. "Ecological Design Applied." *Journal of Ecotechnology*.

Todd, J., E. Brown, and E. Wells. In Publication. "Ecological Design Applied." *Ecological Engineering*.

Tourbier, J. and R. W. Pierson, Jr., eds. 1976. *Biological Control of Water Pollution*. University of Pennsylvania Press., Philadelphia, PA.

University of Wisconsin. 1978. *Management of Small Waste Flows.* US EPA 600/2-78-73. US EPA, Office of Research and Development, Cincinnati, OH.

United States (US) Congress. 1970. *Phosphates in Detergents and the Eutrophication of America's Waters.* House Committee on Government Operations, 1970, 23rd report. US Government Printing Office, Washington, D.C.

United States Environmental Protection Agency (US EPA). 1980. *Design Manual: Onsite Wastewater Treatment and Disposal Systems.* US EPA 625/1-80/012. US EPA, Cincinnati, OH.

US EPA. 1999. *Constructed Wetlands: Treatment of Municipal Wastewaters.* US EPA 625/R-99/01. US EPA. Cincinnati, OH.

US EPA. 2002. *Onsite Wastewater Treatment Systems Manual.* US EPA, Washington, D. C.

US EPA. 2003. *Voluntary National Guidelines for Management of Onsite and Clustered (decentralized) Wastewater Treatment Systems.* US EPA, Washington, D. C.

Vaillant, N., F. Monnet, H. Sallanon, A. Coudret, and A. Hitmi. 2003. "Treatment of Domestic Wastewater by a Hydroponic NFT system." *Chemosphere* 50(1), 121–129.

Vaithiyanathan, P. and C. J. Richardson. 1998. “Biogeochemical Characteristics of the Everglades Sloughs.” *Journal of Environmental Quality* 27, 1439–50.

Ventura Regional Sanitation District. 2001. *Septic Tank Nutrient Removal Project: Advanced Onsite Sewage Disposal System Demonstration.* National Small Flows Clearinghouse, West Virginia University, Morgantown, WV.

Vietor, D. M., E. N. Griffith, and R. H. White. 2002. “Export of Manure Phosphorus and Nitrogen in Turfgrass Sod.” *Journal of Environmental Quality* 31(5), 1731–8.

Vinnerås, B. 2002. *Possibilities for Sustainable Nutrient Recycling by Faecal Separation Combined With Urine Diversion.* Ph.D. Dissertation, Dept. of Agricultural Engineering, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Vinnerås, B., H. Palmquist, P. Balmér, J. Weglin, A. Jenssen, Å. Andersson, and H. Jönsson. Submitted. “The Characteristics of Household Wastewater and Biodegradable Solid Waste—A Proposal for New Swedish Design Values.” *Urban Water*.

Vollenweider, R. A. 1968. *Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication.* Organization for Economic Cooperation and Development, Paris, France.

Wang, J. and D. M. Sievers. 2004. “Phosphorus Removal From Wastewater by Column Adsorption.” *Onsite Wastewater Treatment X, Proceedings of the Tenth National Symposium on Individual and Small Community Sewage Systems, at Sacramento, California.* ASAE, St. Joseph, MI.

West, S. 2001. "Innovations From Scandanavia: Increasing the Potential for Reuse." *Advancing Onsite Wastewater Systems*, Armidale, NSW, Australia.

West, S. 2004. "On-site and Decentralised Sewage Treatment Reuse and Management Systems in Northern Europe & the USA." *Report of a Study Tour - February to November 2000* [Adobe Acrobat file]. S. West 2003 [cited June 27, 2004]. Available from http://www.geocities.com/sarahmwest/osrwwpht.zip.

Wetzel, R. G. 1983. *Limnology.* 2nd ed. Saunders and College Publishing, Philadelphia, PA.

Wilhelm, S. R., S. L. Schiff, and J. A. Cherry. 1994. “Biogeochemical Evolution of Domestic Wastewater in Septic Systems: 1. Conceptual Model.” *Ground Water* 32, 905–916.

Wolverton, B. C. 1986. *Aquatic Plants, Wastewater Treatment, and Wastewater Recovery, July 20–24, at Orlando, FL.*

Zhao, D. and A. K. Sengupta. 1998. “Ultimate Removal of Phosphate From Wastewater Using a New Class of Polymeric Ion Exchangers.” *Water Research* 32(5), 1613–1625.

Zhu, T., P. D. Jenssen, T. Mæhlum, and T. Krogstad. 1997. "Phosphorus Sorption and Chemical Characteristics of Lightweight Aggregates (LWA)—Potential Filter Media in Treatment Wetlands." *Water Science and Technology* 35(5), 103–108.

Zimmo, O. R., R. M. Al-Sa'ed, N. P. Van Der Steen, and H. J. Gijzen. 2002. "Process Performance Assessment of Algae-Based and Duckweed-Based Wastewater Treatment Systems." *Water Science and Technology* 45(1), 91–101.

Zirschky, J. H. and S. C. Reed. 1988. "The Use of Duckweed for Wastewater Treatment." *Journal of the Water Pollution Control Federation* 60, 1253–1258.

6 ACRONYMS AND ABBREVIATIONS

AEC	Anion exchange capacity
Al	Aluminum
ATU	Aerobic treatment unit
BOD	Biological oxygen demand, a measure of organic matter in water
BOD_7	Biological oxygen demand (seven-day test)
BOF	Basic oxygen furnace
Ca	Calcium
CaO	Calcium oxide, or lime
COD	Chemical oxygen demand
COSMO	A computer program that assists users in computing *C*osts of *O*n*S*ite *M*anagement *O*ptions
EQ	Exceptional Quality
Fe	Iron
g	Gram
gal	Gallon
K	Potassium
LPP	Low-pressure pipe
m	Meter
MASSTC	Massachusetts Alternative Septic System Test Center
Mn	Manganese

N	Nitrogen
NaCl	Sodium chloride (table salt)
NaOH	Sodium hydroxide (caustic soda)
NDWRCDP	National Decentralized Water Resources Capacity Development Project
NSF	NSF International (a standards organization)
O&M	Operations and maintenance
P	Phosphorus
P_{tot}	Total phosphorus
P.E.	Person equivalents
pers	person
PLE	Polymeric ligand exchanger
PST	Post-septic tank
QAPP	Quality Assurance Project Plan
SAS	Soil absorption system
SBR	Sequencing batch reactor
TSS	Total suspended solids
TRWQ	Table Rock Water Quality
US EPA	United States Environmental Protection Agency
UV	Ultraviolet light
y	Year

A TECHNOLOGY DESCRIPTION FORMS

Eliminate Garbage Disposals

Manufacturer: Not applicable.

Type of phosphorus-removal technology (check one):

☒ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

Household garbage disposals, or garbage grinders, shred food scraps, vegetable peelings and cuttings, bones, and other food wastes, allowing them to flow through a building's plumbing and into the wastewater treatment system (US EPA 2002). Although the primary concern with garbage disposals involves increased BOD and TSS loadings, they also increase total phosphorus loadings by 2-10%. Eliminating household garbage disposals would divert this phosphorus load from the wastewater stream entering an onsite system.

Technical Description:

Household garbage disposals shred food scraps, vegetable peelings and cuttings, bones, and other food wastes, allowing them to flow through a building's plumbing and into the wastewater treatment system. For any onsite system, the installation of a garbage grinder causes faster buildup of scum and sludge layers in a septic tank and increased risk of organic overloading in the SAS due to higher TSS concentrations in the effluent (US EPA 2002). Although the primary concern with garbage disposals involves increased BOD and TSS loadings, they also increase total phosphorus loadings by 2-10% (University of Wisconsin 1978; US EPA 1980; US EPA

2002; Crites and Tchobanoglous 1998). Eliminating garbage disposals not only reduces the amount of phosphorus entering the system, but also improves system performance by reducing organic loadings, reducing pumping frequencies, and reducing the risk of premature system failure.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**
    - **How long has the phosphorus-removal alternative been used?** Onsite system designers and regulators have been aware of increased phosphorus loadings from garbage grinders since at least the 1950s (Hazeltine 1951), and people have disposed of organic wastes without garbage disposals for millennia.
    - **How many different units have been used?** n/a
    - **Under what conditions have they been used?** Most state regulations require increased septic tank sizes to account for increased loadings from garbage grinders (US EPA 2002). Some states also require increased leachfield sizes, but there is no standard guidance regarding sizing of leachfields to accommodate the grinders.
    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** US EPA 1980 and 2002 onsite design handbooks; wastewater text books; peer-reviewed journal articles.

- **Phosphorus-Removal Capability**
    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** 2-10% of influent phosphorus is removed (0.05-0.27 g P/pers/day) (US EPA 1980; US EPA 2002; Crites and Tchobanoglous 1998). Presence or absence of a garbage disposal is the primary factor affecting phosphorus removal.

  - **How does phosphorus concentration affect removal capability? (Probably not known for most systems and technologies)** n/a

  - **Do other water chemistry factors affect removal capability?** n/a

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** n/a

  - **How does ambient temperature affect the system?** n/a

  - **What range of applications is the alternative designed for?** Household kitchen sinks, although it could also be applicable to institutional facilities, restaurants, etc. that commonly use garbage grinders.

- **Maintenance Requirements**

  - **How often is maintenance required?** n/a

  - **How does lack of maintenance affect system performance?** n/a

  - **What type of maintenance is required? How difficult is it to perform?** n/a

  - **Is there a sorptive material to be replaced?** n/a

    - **If so, how often does this need to be done?** n/a

    - **What are the costs and operations performed when it is replaced?** n/a

- **Is There A Residual to be Disposed of?** Organic kitchen waste

    - **If so, how is it disposed of?** If household garbage disposals are not used, organic kitchen wastes must be disposed of using methods for solid waste disposal (composting, trash collection).

    - **How often is this required, and what are the quantities?** Required regularly as for normal trash collection and management (total kitchen waste ~60 kg/resident/year (Koivula *et al.* 2000). Or may be composted on lot.

- **Phosphorus-Recycling Capability**

  - **How available is the phosphorus removed from wastewater for plant uptake?** If composted, phosphorus from kitchen waste is available for plant uptake. (The general consensus seems to be that about half of household garbage is kitchen waste, but no figures for how much of that goes down the disposal other than EPA/Crites data). If kitchen waste is disposed of as trash, it is generally landfilled, removed from the nutrient cycle, and is no longer available for plant uptake.

- **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** None with properly composted kitchen waste.

- **How concentrated is the phosphorus (this affects economic viability of recycling)?** In composted kitchen waste: 0.40% by weight (Earthmaker NZ); 0.62% by dry weight (Clark 2000)

- **Other Treatment Effects**

  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** n/a

  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal?** Removal of 40-90% of influent BOD; 20-65% chemical oxygen demand; 3-10% total nitrogen; and 70-150% oils and grease (US EPA, 2002).

- **Impact on Landscape**

  - **Is the alternative visible or underground?** If composted outdoors on site, the compost pile is visible. Vermiculture composting is often done indoors.

  - **If it is visible, what is its appearance?** Varies widely. The smallest we are aware of is the Green Cone, approximately 30" high and 20" in base diameter (www.greencone.com). One or two of these is reported to be sufficient for most families.

- **Design**

  - **On what type of sites (soils, etc.) is the technology appropriate to use?** n/a

  - **Any odor issues to consider in siting the technology?** n/a

  - **What are the dimensions (size) of the technology?** n/a

  - **How easily can the technology be used in a retrofit situation?** n/a

  - **Are any changes in user behavior required for this technology to work?** Users must use other methods than garbage grinders for managing kitchen waste.

- **Energy Requirements**

    - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** n/a

    - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** none (unless you count homeowner's energy used to turn compost).

- **Cost**

    - **What is the installation cost?** There is some cost avoidance, both in avoiding the cost of the grinder ($70-$300 or higher) and in reducing the size necessary for the septic system (and/or reducing risk of system failure). The cost of on-lot composting is around $100 for composting bins for a family of four, plus some small expenditure for user education and training, according to composting specialist Tom Anderson at Central Vermont Solid Waste Management District (personal communication). And for apartment dwellers, the cost of a curbside compost pickup service is around $500 per year for a family of four.

    - **What are the operating and maintenance costs?** Virtually none for on-lot composting. For apartment dwellers, around $500 per year for a family of four for the curbside compost pickup.

Phosphorus-Free Dishwasher Detergents

Manufacturer: many

Type of Phosphorus-Removal Technology (check one):

☒ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

The use of phosphorus-free dishwasher detergents reduces the amount of phosphorus entering household wastewater effluent. While 28 states introduced total or partial bans on phosphorus in laundry detergents between 1970 and 1995 as part of their response to increasingly eutrophic surface water conditions, these bans did not extend to dishwashing detergents (Litke 1999; Jones and Hubbard 1986; Correl 1998).

Technical Description:

New powdered laundry detergents developed for washing machines during World War II contained high levels of sodium tripolyphosphate (as much as 60% by weight, or about 15% by weight as phosphorus) as a builder (Litke 1999). Builders generally neutralize hardness in water so that the surfactants in the detergent can function. The detergent industry in the United States voluntarily agreed to limit phosphorus in detergents to 8.7% by weight in 1970 (Litke 1999). While 28 states introduced additional total or partial bans on phosphorus in laundry detergents between 1970 and 1995 as part of their response to increasingly eutrophic surface water conditions, these bans did not extend to dishwashing detergents (Litke 1999; Jones and Hubbard 1986; Correl 1998). In the early 1970s, when phosphorus limits for laundry detergent were set, automatic dishwashers were relatively uncommon. Now that dishwashers are common in many homes, efforts are underway in several states to ban phosphorus in dishwashing detergents as well (Rohrer 1999; Tip of the Mitt Watershed Council 1999; Organization for the Assabet River 2003; Stucky 2003).

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

    - **How long has the phosphorus-removal alternative been used?** 34 years (1970-2004) for limits (Jones and Hubbard 1986); no bans as of this writing

    - **How many different units have been used?** n/a

    - **Under what conditions have they been used?** Corresponded to states that implemented phosphorus bans for laundry detergent; no info available on whether restrictions prompted changes in formulations nationwide

    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** n/a

- **Phosphorus-Removal Capability**

    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).**

      Average detergent use of 90 grams/load was used to calculate grams of phosphorus per load from percentages.

      Assumptions: Average amount of detergent used and average water use per load is unchanged over time in these calculations. No attempt was made to quantify phosphorus from hand washing or manual dishwashing.

      In order to calculate removal percentages, an average automatic dishwasher load volume of 12 gallons was used. Average water use for dishwashers was approx. 1 gal/pers/day (Mayer *et al.* 1999), or about 0.08 dishwasher loads. Calculations for different scenarios are shown in Table A-1.

Table A-1
Calculation of Phosphorus-Removal Potential for Phosphorus-Free Dishwasher Detergents

Scenario	P Content Under Different Scenarios (Percentage Of Influent P Calculated Using EPA 2002 Values)	Amount / % Reduction Of Influent P Achieved By Implementation (Using EPA 2002 Septic Tank Influent P)
a. Historic / commercial (15% P by weight)	1.13 g/pers/day (n/a)	n/a (historic in household scenario)
b. Voluntary limit (8.5% P by weight)	0.65 g/pers/day (24%)	n/a (current situation in household scenario)
c. Max. under ban (0.5% by weight)	0.04 g/pers/day (1.5%)	0.61 g/pers/day (23%)
d. Max. possible reduction (0% P)	0 g/pers/day (0%)	0.65 g/pers/day (24%)

  - **How does phosphorus concentration affect removal capability? (Probably not known for most systems and technologies)** n/a
  - **Do other water chemistry factors affect removal capability?** n/a

- **Robustness of the System**
  - **How is the system's performance affected by variations in flows and in wastewater composition?** n/a
  - **How does ambient temperature affect the system?** n/a
  - **What range of applications is the alternative designed for?** Limits currently only apply to household dishwasher detergent; only implemented in states with phosphorus bans.

- **Maintenance Requirements**
  - **How often is maintenance required?** n/a
  - **How does lack of maintenance affect system performance?** n/a
  - **What type of maintenance is required? How difficult is it to perform?** n/a
  - **Is there a sorptive material to be replaced?** n/a
    - **If so, how often does this need to be done?** n/a

        - **What are the costs and operations performed when it is replaced?** n/a

    - **Is there a residual to be disposed of?** n/a

        - **If so, how is it disposed of?** n/a

        - **How often is this required, and what are the quantities?** n/a

- **Phosphorus-Recycling Capability**

    - **How available is the phosphorus removed from wastewater for plant uptake?** n/a

    - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** n/a

    - **How concentrated is the phosphorus (this affects economic viability of recycling)?** n/a

- **Other Treatment Effects**

    - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** n/a

    - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal?** n/a

- **Impact on Landscape**

    - **Is the alternative visible or underground?** n/a

    - **If it is visible, what is its appearance?** n/a

- **Design**

    - **On what type of sites (soils, etc.) is the technology appropriate to use?** n/a

    - **Any odor issues to consider in siting the technology?** n/a

    - **What are the dimensions (size) of the technology?** n/a

    - **How easily can the technology be used in a retrofit situation?** n/a

    - **Are any changes in user behavior required for this technology to work?** User must purchase and use phosphorus-free dishwasher detergents

- **Energy Requirements**
    - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** n/a
    - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** n/a
- **Cost**
    - **What is the installation cost?** Generally, phosphorus-free or low-phosphorus dishwasher detergents cost more than phosphate-containing detergents (Organization for the Assabet River 2003). Banning phosphorus from dishwasher soap might raise the consumer cost by about 70 cents per box (Stucky 2003).
    - **What are the operating and maintenance costs?** n/a

Phosphorus-Free Laundry Detergents

Manufacturer: many

Type of Phosphorus-Removal Technology (check one):

☒ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

The use of phosphorus-free laundry detergents reduces the amount of phosphorus entering household wastewater effluent. Although laundry detergents containing up to 15% phosphorus by weight were commonly used in the 1940s through the 1960s, many states introduced total or partial bans on phosphorus in laundry detergents in the 1970s and 1980s as part of their response to increasingly eutrophic surface water conditions, particularly in eastern coastal areas and in the Great Lakes states. These bans typically restricted phosphorus levels in detergents to 0.5% or less by weight. Sources conflict regarding the current state of phasing-out of phosphorus in laundry detergent. Some state that the industry ultimately phased out the use of phosphorus in domestic laundry detergents by about 1994, while others state that enforcement efforts were still needed in states with phosphorus bans at least through 1996.

Technical Description:

New powdered laundry detergents developed for washing machines during World War II contained high levels of sodium tripolyphosphate (as much as 60% by weight, or about 15% by weight as phosphorus) as a builder (Litke 1999). Builders generally neutralize hardness in water so that the surfactants in the detergent can function. The use of phosphorus in synthetic detergents peaked in 1967 at 220,000 metric tons (US Congress 1970). The detergent industry in the United States voluntarily agreed to limit phosphorus in detergents to 8.7% by weight in 1970 (Litke 1999). Although no federal legislation restricting phosphorus levels was passed, many states introduced total or partial bans on phosphorus in laundry detergents in the 1970s and 1980s as part of their response to increasingly eutrophic surface water conditions, particularly in eastern coastal areas and in the Great Lakes states. These bans typically restricted phosphorus levels in detergents to 0.5% or less by weight. Although it is generally agreed that the industry ultimately phased out the use of phosphorus in domestic laundry detergents by about 1994 (Litke, 1999), states with phosphorus bans still have problems with high-phosphorus detergents being sold in their states, and enforcement efforts were still necessary in the mid-1990's (Rohrer, 1999).

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☐ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**
    - **How long has the phosphorus-removal alternative been used?** Up to 34 years (1970-2004) (Litke 1999)
    - **How many different units have been used?** n/a
    - **Under what conditions have they been used?** Initially targeted to areas where surface waters were impaired (Great Lakes, Chesapeake Bay (Jones and Hubbard 1986) but eventually phased in everywhere.
    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** n/a
- **Phosphorus-Removal Capability**
    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** Before phosphorus bans and restrictions, laundry detergents contained as much as 15% phosphorus by weight. Currently, a maximum of 0.5% phosphorus by weight is allowed under phosphorus bans in 27 states, while states with no phosphorus ban in force may still use laundry detergents that contain 8.7% or more phosphorus by weight. Average detergent used per load is 2.7 ounces, or 76.5 grams.

Assumptions: Average amount of detergent used and average washing machine load size are unchanged over time in these calculations.

In order to calculate removal percentages, an average washing machine load volume of 40 gallons was used. Average water use for washing machines was approx. 15 gal/pers/day (Mayer *et al.* 1999), or about 0.38 machine loads. Calculations for different scenarios shown in Table A-2.

Table A-2
Calculation of Historic Improvements Gained by Implementing Phosphorus Removal for Household Laundry Detergents

Scenario	P Content Under Different Scenarios (Percentage Of Influent P Calculated Using EPA 2002 Values Unless Noted)	Amount / % Reduction Of Influent P Achieved By Implementation (Using 2002 Influent P Unless Noted)
a. Historic / commercial (15% P by weight)	4.31 g/pers/day (n/a)	n/a (historic in household scenario)
b. Voluntary limit (8.7% P by weight)	2.50 g/pers/day (63% of 1980 influent P)	n/a (current situation in states with no P ban)
c. Max. under ban (0.5% by weight)	0.14 g/pers/day (3.5% of 1980 influent P)	2.36 g/pers/day (59% of 1980 influent P)
d. Max. possible reduction (0% P)	0 g/pers/day (0%)	2.50 g/pers/day (63% of 1980 influent P)

- **How does phosphorus concentration affect removal capability? (Probably not known for most systems and technologies)** n/a
- **Do other water chemistry factors affect removal capability?** n/a

- **Robustness of the System**
  - **How is the system's performance affected by variations in flows and in wastewater composition?** n/a
  - **How does ambient temperature affect the system?** n/a
  - **What range of applications is the alternative designed for? Currently only applies to household laundry detergent**

- **Maintenance Requirements**
  - **How often is maintenance required?** n/a

- **How does lack of maintenance affect system performance?** n/a
- **What type of maintenance is required? How difficult is it to perform?** n/a
- **Is there a sorptive material to be replaced?** n/a
    - **If so, how often does this need to be done?** n/a
    - **What are the costs and operations performed when it is replaced?** n/a
- **Is there a residual to be disposed of?** n/a
    - **If so, how is it disposed of?** n/a
    - **How often is this required, and what are the quantities?** n/a

- **Phosphorus-Recycling Capability**
    - **How available is the phosphorus removed from wastewater for plant uptake?** n/a
    - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** n/a
    - **How concentrated is the phosphorus (this affects economic viability of recycling)?** n/a

- **Other Treatment Effects**
    - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** There is evidence that, in the soil environment, total nitrogen is removed more efficiently from onsite systems that receive phosphate-built laundry detergents rather than carbonate-built detergents (Alhajjar *et al.* 1989).
    - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal?** n/a

- **Impact on Landscape**
    - **Is the alternative visible or underground?** n/a
    - **If it is visible, what is its appearance?** n/a

- **Design**
    - **On what type of sites (soils, etc.) is the technology appropriate to use?** n/a

- **Any odor issues to consider in siting the technology?** n/a
- **What are the dimensions (size) of the technology?** n/a
- **How easily can the technology be used in a retrofit situation?** n/a
- **Are any changes in user behavior required for this technology to work?** n/a

- **Energy Requirements**
  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** n/a
  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** n/a

- **Cost**
  - **What is the installation cost?** Costs for phosphorus-free laundry detergent are not significantly different from those of phosphorus-containing detergents.
  - **What are the operating and maintenance costs?** n/a

Blackwater Diversion

Manufacturer: Can be accomplished by many methods, with products from many manufacturers. On this sheet, we evaluate the potential for phosphorus removal. Specific products are evaluated on other forms.

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☒ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

Technical Description: When phosphates are removed from laundry and dishwashing detergents, the concentration of phosphorus in graywater can be less than 1 mg/L. Phosphorus from the toilet can be transferred either to a less sensitive receiving water or to beneficial use in agricultural through the use of low-flush (≤ 1 L/flush) water toilets plumbed to a holding tank or composting chamber, or through dry toilets plumbed to a composting or holding chamber. The low-flush toilets may use water or foam transported by gravity or vacuum. The graywater may be treated in a variety of ways, including a conventional septic tank and SAS. A high C/N ratio in the graywater may mean that it needs nitrogen addition for typical mixed wastewater treatment processes to work well.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**
  - **How long has the phosphorus-removal alternative been used?** It was the default alternative in most places until the advent of indoor plumbing. Composting toilets were introduced commercially into the United States in the 1970s (Del Porto and Steinfeld 2000).
  - **How many different units have been used?** *See evaluation forms for composting toilets, Aquatron, and microflush toilets.*
  - **Under what conditions have they been used?** Many: cabins, inns, houses, schools, commercial buildings, etc.
  - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** Third-party tests from reports, manuscripts, and peer-reviewed journals.

- **Phosphorus-Removal Capability**
  - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).**

    Assuming that the toilet is used only for defecating and urinating, and not treated as a garbage disposal or mop sink, the mass of phosphorus in blackwater is likely affected somewhat by diet (more phosphorus intake—through protein, phosphoric acid in soft drinks, or other sources—leads to more phosphorus excreted). Flush volumes affect the concentration. For graywater, the amount of phosphate used in detergents is probably the most important factor influencing the mass of phosphorus; water use patterns also affect the concentration. A literature review by Rasmussen *et al.* (1996) found graywater phosphorus concentrations from 1.4 - 18.1 mg/L.

    A report by the Swedish EPA (Swedish EPA 1995) put the Swedish annual output of phosphorus in graywater at 110 grams/person/year (g/p/yr), or 17% of the total phosphorus in domestic wastewater. Vinnerås *et al.* (Vinnerås *et al.* submitted) proposed a higher average Swedish annual phosphorus output from graywater, at 190 g/p/year and that the earlier figure for blackwater was accurate, giving 25% of phosphorus in graywater.

Jenssen and Vråle (Jenssen and Vråle 2003) report that graywater septic tank effluent samples taken after 1996 in Norway, representing almost 200 persons, showed average P_{tot} concentrations of 1.03 mg/L. This is about 20-50% of what is reported in neighboring Sweden (calculated from (Swedish EPA 1995) and (Vinnerås *et al.* submitted)); Jenssen and Vråle note that the majority of laundry and dishwashing detergents sold in Norway are phosphate free, whereas they contain phosphate in Sweden.

Otterpohl *et al.* (2002) survey two German and Swiss articles from the late 1990s and a compilation of many earlier studies published in 1981 to arrive at a German figure of 750 g P/p/yr, with 90% in the blackwater.

Sherman's review of the US literature (1991) found a "weighted value" of 3 mg/L P_{tot} in the seven studies he reports on, from 1968-1978. Blackwater has a *lower* phosphorus strength (<1 mg/L) than graywater in these studies. Like recent values from other countries, these older values are probably not representative of current US values, since legislation restricting phosphate use in detergents has been passed since then and low-flow fixtures have become more widespread.

The US EPA's *Onsite Wastewater Treatment System Manual* (2002, Table 3-8) reports that 59% of phosphorus in domestic wastewater is from the toilet, using figures from Sedlak (1991). Because of the effect of changes in detergent composition on phosphorus flows, the EPA ignores earlier studies as being unrepresentative of today's flows. If 27% of domestic wastewater is from toilet flushing (Table 3-3, US EPA 2002), then the concentration of phosphorus in graywater is (1-0.59)/(1-0.27) = 55% of that in domestic wastewater as a whole. With a range of 5-15 mg/L for phosphorus in domestic wastewater (Table 3-19, US EPA 2002), that gives a range of 3-8 mg P/L in graywater.

A recent literature survey by Siegrist *et al.* (Siegrist *et al.* In press.) documents a decrease in phosphorus concentration in septic tank effluent from the 1970s through the 1990s, with values in the 1990s ranging from 1.2-14.2 mg/L, with the average 8.4 mg/L.

- **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** The literature generally includes values for P_{tot}, and sometimes has values for phosphate.

- **How does phosphorus concentration affect removal capability?** Not at all, per se. However, if a higher phosphorus concentration is a function of greater use of phosphates in detergents, then the percentage removal by removing the blackwater from the treated flow is less.

- **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** No.

- **Robustness of the System**
  - **How is the system's performance affected by variations in flows and in wastewater composition?** No effect.
  - **Under what climatic conditions were the tests conducted?** Not applicable
  - **How does ambient temperature affect the system?** No effect.
  - **What range of applications is the alternative designed for?** Anywhere with toilets. It is especially effective for phosphorus removal where blackwater comprises a significant part of the wastewater phosphorus load.
- **Maintenance Requirements** *See evaluations of individual technologies.*
- **Phosphorus-Recycling Capability** *See evaluations of individual technologies.*
- **Other Treatment Effects**
  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** The C/N ratio in graywater is higher than that in mixed wastewater. According to Del Porto and Steinfeld (Del Porto and Steinfeld 2000), this can lead to the build-up of "undigested carbon-containing fats, oils, grease, soaps, detergents," and other substances. They suggest adding some nitrogen to the graywater, through ammonia-based cleaning compounds, nitrogen fertilizer, or diverting some of the urine to the graywater.
  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** Removing blackwater from domestic wastewater treated on site diverts a higher percentage of nitrogen than of phosphorus; the studies referenced above report 90% or more of the nitrogen in domestic wastewater is in the blackwater. Around half of the organic matter (measured as COD or BOD) is also removed, according to the studies referenced above.
- **Impact on Landscape** Not applicable
  - **Design**
  - **On what type of sites (soils, etc.) is the technology appropriate to use?** No site limitations *per se* for blackwater diversion. Unless graywater is treated and recycled, as in the Equaris Infinity system, some graywater treatment and dispersal system is needed. With composting toilets, provision needs to be made for excess liquid—usually treatment and dispersal.

- **Any odor issues to consider in siting the technology?** The Swedish EPA (2002) refers to an earlier Swedish EPA report that found more odor issues from cabins treating graywater than from those treating mixed wastewater. The study may have been referring to simpler graywater treatment systems, (e.g., Ludwig 2000). No other reports of excessive odors from graywater have been found.

- **What are the dimensions (size) of the technology?** *See evaluations of individual technologies.*

- **How easily can the technology be used in a retrofit situation?** *See evaluations of individual technologies.*

- **Are any changes in user behavior required for this technology to work?** Not necessarily. *See evaluations of individual technologies.*

- **Energy Requirements** *See evaluations of individual technologies.*

- **Cost** *See evaluations of individual technologies.* Blackwater diversion is most cost effective if there are significant barriers to putting in a conventional septic tank and SAS system.

Composting Toilet

Manufacturer: Many.

This description is a composite of systems that have long track records and are available in the US.

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☒ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

Description: The term "composting toilet" encompasses a wide range of technologies. The common feature is that the feces are collected and retained in the toilet system—either in a chamber of the toilet itself or in a separate chamber, generally in a room below the toilet. The feces may be composted in the toilet system itself or merely collected and retained there, for composting or other treatment elsewhere. Composting toilets differ from pit privies, or outhouses, in that composting toilets are designed for a partially or completely composted product to be periodically removed from the system.

The collection system is usually gravity, though microflush toilets (<0.1 - 0.5 gal/flush), using either water or foam, are also being attached to composting chambers. Urine may be collected separately, in urine-diverting composting toilets. If urine is not diverted, it may be evaporated during the composting process, or (along with flush water, if any) it may be channeled out of the composting chamber for treatment or use as fertilizer elsewhere.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**
  - **How long has the phosphorus-removal alternative been used?** The modern, in-house composting toilet is generally traced back to the Swedish Clivus Multrum, invented by Rickard Lindström in the 1930s and patented in 1962. During the 1800s, however, commercially sold "earth closets" by Henry Moule and others in Britain competed fiercely with the water closet and may be the first manufactured composting toilets (Del Porto and Steinfeld 2000). Composting toilets have been available in the US commercially since 1964 (Del Porto and Steinfeld 2000) and are used both in single-family residences and apartments as well as commercial and other buildings (Berger 2004; Del Porto and Steinfeld 2000; Panesar and Lange 2004).
  - **How many different units have been used?** There is no trade association for composting toilet manufacturers in US, so data are hard to come by. A rough estimate from Don Mills of Clivus Multrum is that 5,000 composting toilets have been sold in the US in the last decade by all manufacturers (Mills 2004). Tens of thousands have been sold worldwide in the last forty years (Del Porto and Steinfeld 2000).
  - **Under what conditions have they been used?** In different forms, from the tropics to the Arctic, in residential, commercial, and public facilities.
  - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** *See discussion in the "Blackwater diversion" evaluation form.*
- **Phosphorus-Removal Capability:** *See discussion in the "Blackwater diversion" evaluation form.*
- **Robustness of the System**
  - **How is the system's performance affected by variations in flows and in wastewater composition?** Del Porto and Steinfeld (2000) say that, in general, leachate collects during normal use of composting toilets, even those with evaporators, not just during power outages or peak use.
  - **Under what climatic conditions were the tests conducted?** They are designed primarily for use indoors, so climate plays a minor role in the performance.
  - **How does ambient temperature affect the system?** Warmth promotes composting. Some have or may be fitted with a heating element. According to one manufacturer

(personal communication, David Del Porto, EcoTech), room temperature of 65 degrees F is sufficient for composting at an adequate rate.

- **What range of applications is the alternative designed for?** Composting toilets are available for any applications where water closets are used. The models described in detail here are all designed for loading comparable to residential use. Models are available for use in public facilities.

- **Maintenance Requirements**

  - **How often is maintenance required?** Depending on the model, minor operation (turning a handle) may be needed as often as 3-4 times a week. Compost is emptied as often as once a month for a self-contained model or every three months to two years for models with larger composting chambers in a separate room.

  - **How does lack of maintenance affect system performance?** Flying insects may enter the house, since there is no trap or other barrier between the composter and the toilet room (Del Porto and Steinfeld 2000). In one model, the pile compacts and becomes too hard to remove through the access hatch through normal means. In another, the composting chamber simply becomes too full to accept more material.

  - **What type of maintenance is required? How difficult is it to perform?** Maintenance is not difficult to perform if it is kept up regularly. For the models with separate compost chambers, it is important that the unit be placed so that the access hatch is easy to get to and use. One model reviewed continues to accept new material even when not maintained, and it can get filled with a compacted, difficult-to-remove mass before the user is given hard-to-ignore feedback that something is wrong.

  - **Is there a sorptive material to be replaced?** No.

  - **Is there a residual to be disposed of?** Yes.

    - **If so, how is it disposed of?** Laws on handling composted human excrement vary in different locations. Options include burying it on site or hauling to a wastewater treatment plant. Del Porto and Steinfeld (2000) recommend contacting local and state health authorities for information on legal methods for handling the end product of a composting toilet. They give the example of Massachusetts, where the compost may be buried on site under six inches of soil or removed to a treatment plant by a licensed septage hauler. The compost may be claimed as fertilizer, they report, if it is tested for bacteria, viruses, and heavy metals according to Part 503 of Section 450 of the Clean Water Act.

    - **How often is this required, and what are the quantities?** Varies with usage and system design. One manufacturer says that the composted material is about one tenth the bulk of the incoming excrement, toilet paper, and additive (bulking material) (US EPA 2003), and the US EPA reports that if "sized and maintained properly, a composting toilet breaks down excrement to 10 to 30% of its original volume" (US EPA 1999). Another manufacturer says its toilet can reduce the volume of urine plus feces to much less than 10%.

- **Phosphorus-Recycling Capability**

  - **How available is the phosphorus removed from wastewater for plant uptake?** No specific data; probably as available as in composted livestock manure.

  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** The composted material needs to reach pasteurization temperatures to be assured that pathogens are killed. Jenkins (1999) reports that a compost pile fed with uncomposted human feces, urine, toilet paper, bulking material, garden weeds, and kitchen scraps consistently reaches pasteurization temperatures in a cold climate (Pennsylvania). Over the winter, accumulation without pasteurization occurs until spring. Del Porto and Steinfeld (2000) caution against using the composted material on food crops.

  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** No specific figures found. If the mass of urine, feces, and toilet paper is reduced to 10%, then the concentration is 1.365 kg P/ 60.9 kg = about 2% (figures from (Vinnerås *et al.* submitted)).

- **Other Treatment Effects**

  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** No, except as per next question.

  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** Yes. See "Blackwater diversion" evaluation form for details.

- **Impact on Landscape**

  - **Is the alternative visible or underground?** Usually in the house.

- **Design**

  - **On what type of sites (soils, etc.) is the technology appropriate to use?** All

  - **Any odor issues to consider in siting the technology?** If urine is not diverted from the compost, then the ventilated exhaust can be foul smelling. This can be particularly a problem where houses are close together in a steep area, so the ventilation pipe of a lower house is near the living level of an upper house. Odor can be reduced or removed through use of odor control additives on the compost heap and/or filtering the exhaust through activated carbon, zeolite, or other material (Del Porto and Steinfeld 2000).

- **What are the dimensions (size) of the technology?** Many models of different dimensions are available. For example, one separate compost chamber dimensioned for sixty visits per day is 60" high, 104" deep, and 47" wide (Del Porto and Steinfeld 2000). A self-contained toilet unit is 33" high, 23" wide, and a depth of 47" is needed to allow room to open and remove the finishing drawer**.**

- **How easily can the technology be used in a retrofit situation?** Self-contained units are easier to use in most retrofit situations than ones that have a composting chamber in a room below.

- **Are any changes in user behavior required for this technology to work?** Yes. All three models require addition of bulking material with each use. In addition, periodic maintenance is required, as described above. One manufacturer does offer maintenance contracts, mostly to public installations, but they also have maintenance arrangements with residential customers, usually with visits twice yearly. Diligent addition of the bulking material after each use, and perhaps other measures (e.g., covering exhaust pipe terminus with screen, light traps, sticky traps), is required to prevent or eliminate the spread of flying insects into the house (Del Porto and Steinfeld 2000).

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.**

    800-1,500 kWh/year to power an exhaust fan, leachate pump, and, if used, a heating element.

  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."**

    A small amount of composted material is removed periodically, depending on the toilet system and the usage. For example, if one model examined is used enough to be emptied every three months and the volume of the compost is reduced to one tenth of the original, full compartment volume, then 12 gallons of finished compost would be removed every three months. The finished compost may be buried near the house or transported elsewhere, depending on user preferences and local ordinances.

- **Cost**

  - **What is the installation cost?** Approximately $1,600 - $6,400, depending on the model.

  - **What are the operating and maintenance costs?** All normal maintenance can be performed by most able-bodied users, if the composting chamber is properly installed. Electricity for the exhaust fan, heater (if any), and any other equipment is the only operating cost. Using the average national 1999 electricity cost of 6.6 cents per kWh (US Department of Energy 2003), the annual operating costs are generally $25 – $87. This brings the total life-cycle costs to $3,600 - $7,600 over the cost of a conventional system.

  - On lots where there is no space to install a full-size conventional system and local regulations allow graywater systems to be smaller than full-sized systems, the composting toilet can save money over any other feasible alternative (examples given in Del Porto and Steinfeld 2000).

Aquatron

Manufacturer: Aquatron International, Amberes AB

Box 65
SE-456 22 Kungshamn, Sweden
Phone: +46 523 709 66
Fax: +46 523 709 67

Office address:
Dalgatan 4
Kungshamn, Sweden

info@aquatron.se

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☒ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

Aquatron separates the fecal water (with or without urine) from a toilet into solid and liquid fractions, using the whirlpool effect of the spiralling of the flushed water in the Aquatron separator. The solid fraction is composted in the Aquatron; the product from some models is ready for use as compost when removed from the Aquatron, while the manufacturer recommends further composting when using the product from other models.

Technical Description:

The Aquatron can be used on the flush water from either urine-diverting toilets or toilets where urine and feces are mixed. It is designed for toilets of 2-6 liters flush volume; new US toilets have a maximum of 6 L flush volume. The distance between the toilet and the Aquatron separator is a minimum of 1 meter pipe, and maximum 10 or 20 meters (depending on whether 2 or 6 liters are used for flushing), with a minimum 1% slope, except for a minimum 5% slope in the last meter.

The separator is a plastic unit shaped like an hourglass. The incoming water spirals around the sides of the hourglass. As the water passes through the narrow middle of the "hourglass," solid matter like feces and toilet paper fall straight down, into an opening of the composting chamber. The water continues adhering to the side of the hourglass and exits the bottom. No moving parts are used; the momentum of the flushed water imparts all the spiraling. After exiting the separator, the water may go through UV-disinfection and may be combined with graywater for treatment in a septic tank and soil absorption system.

The solids are stored in a "Bio Chamber," where they are composted using bacteria and, if desired, the addition of worms. Composting reduces the volume by up to 90%, according to the manufacturer.

Units of various sizes are manufactured. While some are manufactured for commercial facilities and apartment buildings, all are designed to handle the toilet water within a fairly short distance of the toilet, usually inside the same building as the toilet. For that reason, if the technology is to be used with cluster systems, each building connected to the cluster system would have its own Aquatron, and larger commercial buildings may use more than one.

UV lights for disinfecting the effluent are available.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

    - **How long has the phosphorus-removal alternative been used?** The company was founded in 1992.

    - **How many different units have been used?** According to the manufacturer, "thousands." West (2001) reports 1500 in New Zealand alone.

- **Under what conditions have they been used?** Residences, apartment buildings.

- **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** Third-party tests were carried out by Björn Vinnerås of the Swedish Agricultural University. They comprised both tests of a unit in use at an apartment building and laboratory tests. Unless otherwise noted, all figures in this evaluation form are from Vinnerås (2002), including the appendices.

- **Phosphorus-Removal Capability**

  - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** Vinnerås (2002) notes from his lab experiments that "an increased loss of nutrients will also occur if water is drained from the separated solids." In actual installations, the Aquatron is designed to let the separated solids be further dewatered by draining. The 13% phosphorus-removal potential is, therefore, probably higher than phosphorus removal in the field.

  - **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** P_{tot}

  - **How does phosphorus concentration affect removal capability?** Aquatron removes the solid fecal matter and toilet paper from the wastewater stream. Removal capability is affected by how much phosphorus is in the feces.

  - **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** No.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** Toilets with higher flushing volumes (6 L vs. 4 L) reduce the amount of dry matter captured by Aquatron. Wastewater with less solid matter in it (e.g., because of diarrhea) would presumably have less effective phosphorus removal. No information has been found on the effect of variations in wastewater flows. However, given that Aquatron does its work in the seconds immediately after flushing, there is no reason to expect performance to be affected by variations in flows, except perhaps if two toilets connected to the same separator are flushed within seconds of each other.

  - **Under what climatic conditions were the tests conducted?** Conducted inside of buildings.

  - **How does ambient temperature affect the system?** The manufacturer recommends that the Aquatron be kept at temperatures above freezing. Warmer temperatures promote faster composting.

- **What range of applications is the alternative designed for?** Could be used in most places where there are toilets. The recommended maximum pipe run of 20 m from toilet to Aquatron limits the use in taller or sprawling buildings, unless many units are installed.

- **Maintenance Requirements**

  - **How often is maintenance required?** In the simplest units, the solids are removed when the unit is filled. According to the manufacturer, this is every year or two for a model for year-round, single-family homes, the Aquatron 400. The reports of West (2003) on uses of the Aquatron agree. The UV lights need to be replaced periodically in units where they are used.

  - **How does lack of maintenance affect system performance?** When the unit is filled and not emptied, the fecal matter runs out of the unit.

  - **What type of maintenance is required? How difficult is it to perform?** Removal of partially or completely composted solids. Some larger units have mechanical systems to move the compost around. No information was found on the difficulty of removing the solids. It is important that the unit be placed so that the access hatch is easy to get to and use.

  - **Is there a sorptive material to be replaced?** No

  - **Is there a residual to be disposed of?** Yes, the partially or completely composted solids.

    - **If so, how is it disposed of?** Can be treated as septage, or further composted, on site or off site, depending on local regulations.

    - **How often is this required, and what are the quantities?** The manufacturer reports every 1-2 years for a single-family home. Given the dimensions of the unit, the quantity is estimated to be no more than 150 L (40 gallons). (The manufacturers claim that the composting reduces volume by up to 90%.)

- **Phosphorus-Recycling Capability**

  - **How available is the phosphorus removed from wastewater for plant uptake?** No specific data found. Presumably, as available as in composted livestock manure.

  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** No tests on the pathogen content of the fecal matter (partially or completely composted) have been found. Since there is little or no separation of fresh and old material, further treatment for pathogen reduction would almost certainly be necessary before using the material in agriculture.

The following are the standard values for heavy metals in feces, as used in Sweden (Vinnerås *et al.* submitted):

Table A-3
Swedish Standard Values for Heavy Metal Content in Feces

Metal	Content in Feces (mg/pers/yr)
Cd	3.7
Cu	400
Cr	7.3
Hg	23
Ni	27
Pb	7.3
Zn	3900

Source: (Vinnerås *et al.* submitted).

The Swedish standard value for feces production is 12.8 kg dry matter/year (Vinnerås *et al.* submitted). If composting reduces mass by 90% with no loss of heavy metals, the following table shows the relationship between the concentration of heavy metals in uncomposted vs. composted feces and the US EPA values for EQ (exceptional quality) sewage sludge and the US EPA ceiling levels for sewage sludge applied to land (all units mg/kg):

Table A-4
Heavy Metal Content in Feces and Composted Feces Compared With Limits for US EPA's EQ Sludge and EPA's Ceiling for Land-Applied Sludge

Metal	Fecal Dry Matter	Composted Fecal Dry Matter	EPA EQ Sludge	EPA Ceiling Limit
Cd	0.29	2.9	39	85
Cr	0.57	5.7	NA	NA
Cu	31	310	1500	4300
Hg	1.8	18	17	57
Ni	2.1	42	420	420
Pb	0.57	11	300	840
Zn	300	6000	2800	7500

The US EPA also regulates arsenic and molybdenum levels in sludge applied to land (Harrison *et al.* 1999); no figures were found on the levels of these metals in feces.

In short, for all metals in sewage sludge regulated by the US EPA and for which figures on the fecal content have been found, the composted fecal dry matter is below EQ sludge limits, except for zinc. Zinc is below the EPA ceiling limit.

- o **How concentrated is the phosphorus (this affects economic viability of recycling)?** The initial dry matter content of the separated solids, after 3 meters of pipe and with 4 L flushing water, is 10%.

- **Other Treatment Effects**

  - o **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** No chemical change. Solids are removed.

  - o **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** Organic matter and suspended solids content are surely reduced through removal of fecal matter, though no tests to verify this were found.

- **Impact on Landscape**

  - o **Is the alternative visible or underground?** Usually in the basement.

  - o **If it is visible, what is its appearance?** The Aquatron separator itself is plastic, hourglass-shaped, about 50 cm high and 40 cm in diameter. The version for a single-family home, the Aquatron 400, is 145 cm high (without UV unit), 80 cm wide, and 120 cm deep, including the separator and composting facility.

- **Design**

  - o **On what type of sites (soils, etc.) is the technology appropriate to use?** Any.

  - o **Any odor issues to consider in siting the technology?** None reported.

  - o **What are the dimensions (size) of the technology?** The Aquatron separator itself is plastic, hourglass-shaped, about 50 cm high and 40 cm in diameter. The version for a single-family home, the Aquatron 400, is 145 cm high (without UV unit), 80 cm wide, and 120 cm deep, including the separator and composting facility.

  - o **How easily can the technology be used in a retrofit situation?** It is designed for blackwater only, so dividing the plumbing might be tricky. West (2003) reports that an ecovillage in England plumbs mixed graywater and blackwater through their

Aquatrons, but we have no reports on phosphorus removal performance from that facility.

- **Are any changes in user behavior required for this technology to work?** No, not for use of the toilet. If the user empties the compost chamber, that is a change, but that is a service that can be provided by a service provider, like pumping out a septic tank.

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** None

  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** The compost chamber is emptied every year or two and contains max. 40 gallons of compost for a single-family unit. The manufacturer claims up to 90% reduction in volume when worms are used in the composting process. The compost may be used on site.

- **Cost**

  - **What is the installation cost?** Approximately $1,600, based on the cost for the unit in the United Kingdom (no costs in the US were found) and shipping and installation costs provided by the manufacturer.

  - **What are the operating and maintenance costs?** No figures available. Presumably minimal, if the unit is situated so that there is easy access to the compost chamber. It is emptied of at most 40 gallons every 1-2 years, and this is work the user can easily perform. If the user empties the compost, the life-cycle cost above a conventional system is equal to the installation cost, $1,600; with a maintenance contract to empty the compost costing $300 per year, the life-cycle cost is $8,400.

Microflush Toilet

Manufacturer: Many. A number of models were chosen for evaluation, based on their track record and the appropriateness of their design for domestic use.

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☒ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

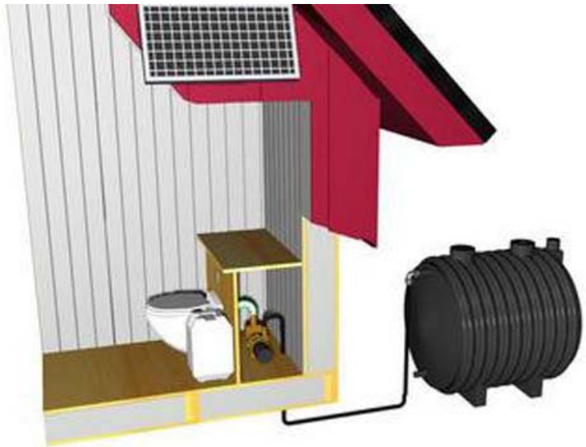
☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description: Microflush toilets are a type of blackwater diversion strategy. Using small amounts of water, the toilets make it possible to connect blackwater to a holding tank and fill the tank much less frequently than if all the plumbing were collected in the holding tank. The concentrated blackwater may be transported off site for treatment elsewhere, which may include liquid composting for reuse in agriculture. If all blackwater is diverted, then about 75% of the phosphorus in domestic waste is removed.

Technical Description: The microflush toilets described here are all vacuum toilets, which use air to transport feces and urine, in the same way as toilets commonly used on airplanes, cruise ships, and trains. Use of vacuum to transport the waste greatly reduces the need for water, and it also makes strictly horizontal or even uphill pipe runs possible. Air is the primary transport mechanism for the feces, urine, and toilet paper, with water used primarily to clean the bowl and the pipes. Some systems keep a continuous vacuum in the pipe, and instead of a conventional plumbing trap, a mechanical trap is used. When the toilet is flushed, an electronic valve is opened in the trap, and the contents of the toilet bowl are transported by the vacuum in the pipe to the vacuum generator, which then pushes the urine, feces, and toilet paper with pressure to the holding tank. (See Figure A-1, below.)



Source: http://www.folkeweb.no/cgi-bin/webadm.cgi?gid=1022&c=1058

Figure A-1
A Vacuum Toilet With the Vacuum Generator Behind the Toilet and the Holding Tank Outside the House

Other systems generate vacuum on demand, i.e., only when a toilet is flushed. One model is available in a urine-diverting version.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

Most of the information is from the manufacturers, either product literature or interviews.

What is the appropriate application of this alternative? Check as many as apply:

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

Note: The microflush toilet systems profiled here are most appropriate for buildings with small numbers of toilets, up to 10. Some manufacturers build vacuum generators capable of handling larger numbers of toilets, which may be more cost effective for larger numbers of toilets.

- **Proven Track Record**

  How long has the phosphorus-removal alternative been used?
  The Swedish engineer Joel Liljendahl patented a vacuum toilet in 1956. Electrolux bought the patent rights in 1968 and developed the technology further (Grünert 1999; cited in Backlund and Holtze 2003)

  - **How many different units have been used?** The major manufacturers often produce over 10,000 per year. Most of the toilets manufactured are designed for marine uses, so terrestrial experience is not as extensive.

  - **Under what conditions have they been used?** In buildings: Apartments, dormitories, institutions (e.g., prisons, hospitals), renovated buildings (where uphill runs of wastewater lines can make it possible to use the space in a different way), cottages. Microflush vacuum toilets are more common on airplanes, trains, boats, and ships.

  - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** *See blackwater diversion evaluation form.*

- **Phosphorus-Removal Capability** *See blackwater diversion evaluation form.*

  - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).**

  - **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.**

  - **How does phosphorus concentration affect removal capability?**

  - **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?**

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** The toilet systems are not at all sensitive to variations in flow and wastewater composition, the manufacturers report, as long as foreign objects are not flushed.

  - **Under what climatic conditions were the tests conducted?** The toilets have been used in marine environments and in the far north, as well as various parts of the US and the Mediterranean region.

  - **How does ambient temperature affect the system?** No effect for temperatures above freezing, according to the manufacturers.

What range of applications is the alternative designed for? Residences, commercial buildings, institutions, cottages. Pretty much anywhere a conventional toilet is used, and especially where water is scarce or plumbing toilets uphill is desirable. One model uses so little water per flush (0.5 L or 0.25 L, depending on whether one is flushing urine or feces) that it is designed with the option of installing it in a cottage with no running water. An attachment is available to draw flush water from a bucket carried into the house; a 10 L (2.6 gal.) bucket is enough to flush 20-40 times. Manufacturers sell vacuum generators which operate from a 12 V DC power supply, so that a photovoltaic cell and battery can provide the electricity.

- **Maintenance Requirements**

How often is maintenance required? The holding tank must be emptied. The frequency varies with the amount of water used; see table with residual discussion, below. Otherwise, rubber valves or membranes need to be replaced every 3-15 years, say the manufacturers. In heavily used systems, or if solid objects like rings or coins get flushed, the vacuum generator may need to be cleaned occasionally.

In home systems using small amounts of flush water, urine stone may build up on some of the pipes. The manufacturer says the pipe may need to be replaced every twenty years.

How does lack of maintenance affect system performance? If the holding tank is not emptied, it overflows. Otherwise, if never replaced, the mechanical trap could eventually leak air, and the vacuum generator will cycle on more often. If the flush ball seal is not cleaned and hard water depositions build up, the mechanical trap could also leak. Similarly, if urine stone grows on the inside of the pipes, they will clog more easily and the vacuum generated will have less power to flush.

- **What type of maintenance is required? How difficult is it to perform?** Manufacturers say that "any shade tree mechanic would have absolutely no difficulty" replacing the four rubber valves at the vacuum generator or "anyone" can replace a mechanical trap. Cleaning the toilet appears no more difficult than for a conventional WC, though cleaning the mechanical trap is a different process than for a conventional WC. The manufacturer of one vacuum-on-demand system recommends that the valve on the vacuum generator be replaced by a professional.

- **Is there a sorptive material to be replaced?** No.

- **Is there a residual to be disposed of?** Yes, the blackwater.

  - **If so, how is it disposed of?** Can be treated as septage. Alternatively, the high dry matter content makes it attractive for use in liquid composting, where facilities are available, and reuse the nutrients in agriculture (see, for example, Skjelhaugen 1999; Norin *et al.* 2000). Liquid composting is an aerobic process that can be managed to attain 60 °C for 24 hours, which effectively pasteurizes the liquid. Only limited use of liquid composting facilities has been found in the US (e.g., Patterson and Short 1985; Deeny *et al.* 1991).

- **How often is this required, and what are the quantities?** The smallest amount of flush water found was in a toilet with a button for a 0.5 L (17 oz.) flush (for feces) and a button for a 0.25 L (8 oz.) flush (for urine). Another popular vacuum toilet can nominally be set as low as 16 oz. per flush, but the manufacturer says that 24 oz. is a more realistic figure. With these volumes, the toilet could be flushed 3,800 – 6,700 times before a 1,000 gallon holding tank was 90% filled, a target that might be chosen for an alarm to signal that it is time to schedule a tank pumpout[3].

- **Phosphorus-Recycling Capability**
  - **How available is the phosphorus removed from wastewater for plant uptake?** After liquid composting, about 60% of the nitrogen is available to plants as ammonium (Norin 1996). Without liquid composting, presumably the same phosphorus availability as for septage, but we have found no data.
  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** *See blackwater diversion evaluation form.*
  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** Depends on volume of flush water and where the toilet is used. Urine concentration often varies throughout the day, and there are indications that feces may be excreted primarily in the home toilet. Assuming a high enough proportion of the toilet visits are in the home toilet that the average phosphorus concentration per toilet visit is representative of total daily urine (e.g., for someone with a home business), and assuming 8 toilet visits per day, then the concentration is 0.13-0.36 g/kg for the toilets evaluated here.
- **Other Treatment Effects** *See blackwater diversion evaluation form.*
- **Impact on Landscape**
  - **Is the alternative visible or underground?** Vacuum generators and holding tanks can be in the building or underground outside. See also discussion of ambient temperature, above.

[3] The calculation assumes 8 toilet visits per day, that the amount of feces and urine correspond to the "BV" figures in Table 2-4.

- **Design**

  - **On what type of sites (soils, etc.) is the technology appropriate to use?** Any.

  - **Any odor issues to consider in siting the technology?**

    Yes. One manufacturer recommends that deodorants be used to prevent odors in the holding tank. Another says that odor is potentially somewhat more than with a normal septic tank, since many gallons of air are being forced into the tank with each flush. The tank should be vented to over the roof of the house.

  - **What are the dimensions (size) of the technology?** The toilets are standard size. The holding tanks can be in a wide range of sizes. For the vacuum generator, one manufacturer has various sizes (H × W × L): 14 × 8 × 19", 7.5 × 10 × 29". Another vacuum generator is 11.6 × 6.4 × 14.2", while a third is 17.7" high and 10.2" in diameter.

  - **How easily can the technology be used in a retrofit situation?** One of the most cost-effective ways to use vacuum toilets is in building renovations, according to one manufacturer. The ability to run the pipes without constant fall, even going uphill, gives builders much more flexibility, especially in adding new toilets.

  - **Are any changes in user behavior required for this technology to work?** The toilets function similarly to conventional, gravity water closets, from the user's perspective. The flushing procedure is slightly different, but easy to learn. There is some delay between the user pushing the flush button or pulling the handle and the flush actually happening, from a few seconds to 15 seconds, depending on the size of the system. It is at least as important as with gravity toilets, probably more important, not to put foreign objects down the toilet. When cleaning the toilets with mechanical traps, it is important to be careful of the mechanical trap. The manufacturers recommend that toilet paper low in adhesives be used, to avoid clogging, and one sells a toilet paper designed to work well with their system. The toilets make a different sound than conventional WCs, and the vacuum generator makes a noise.

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** 2-5 kWh/person/year, according to the manufacturers.

  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can**

use a common set of assumptions for each technology to convert to energy use. E.g., “The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant.” See discussion on residual, above.

- **Cost**

    - **What is the installation cost?** For the toilet, vacuum generator, and an extra 1,000 gallon tank $3,900 - $5,800.

      What are the operating and maintenance costs? The volume of flush water, and therefore frequency of tank emptying, dominates the operations and maintenance costs. All normal maintenance can be performed by most somewhat handy users, say the manufacturers, so no cost has been included for the time. Electricity for the vacuum generator plus emptying the tank are the only operating costs. Assumptions: the average national 1999 electricity cost of 6.6 cents per kWh (US Department of Energy 2003), four persons in the household each using the toilet six times per day, and $380 to empty the tank. Then the annual operating costs are $1,300 - $1,800. The estimated life-cycle cost, then, is $35,000 - $44,000 over that of a conventional system.

Infinity Water Recycling System

(formerly known as Equaris, and before that as AlasCan water recycling system)

Manufacturer: **Equaris Corporation**
www.equaris.com
Phone: (651)-337-0261
Fax: (651)-337-0265

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☒ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

Compete recycling unit in which water can be treated onsite and, if disinfection unit is included in the package, treated graywater can be reused as drinking water, according to the manufacturer. Water discharge is only necessary when dissolved solid concentrations reach an unacceptable level for drinking water.

Technical Description:

A separation tank, extended aeration treatment system, and disinfection tank are used to convert waste to biomass and, according to the manufacturer, potable water. Ninety-five percent of solids in the separation tank are converted to carbon dioxide and water vapor. The resulting solid biomass (~19,000 mg P/dry kg) can be used as fertilizer. A microflush water toilet is plumbed to a composting chamber. The composting chamber also receives kitchen waste and sludge from the graywater treatment system. The graywater is treated using a combination of settling, extended aeration, filtration, reverse osmosis, and ultraviolet light, and recycled within the house. Six prototypes have been installed.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☐ Large system, over 3,500 gallons per day

☐ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**
    - **How long has the phosphorus-removal alternative been used?** No information
    - **How many different units have been used?** 6-7 fully recycling operations in use (personal communication, Clint Elston, Equaris Corp. 2004).
    - **Under what conditions have they been used?** Located inside.
    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** Not applicable, no discharge. Phosphorus concentration in solid biomass given by manufacturer.

- **Phosphorus-Removal Capability**
    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** Effectively 100%, since no water is discharged. However, in systems which provide drinking water, build up of dissolved solids and salt require water to be discharged into SAS or other treatment facility. No data available for phosphorus levels in water (personal communication, Clint Elston, Equaris Corp. 2004).
    - **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** Total phosphorus per mass of dry end product.
    - **How does phosphorus concentration affect removal capability?** Not known.
    - **Do other water chemistry factors (e.g. pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** No.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** Effect not known

  - **Under what climatic conditions were the tests conducted?** Indoors

  - **How does ambient temperature affect the system?** Not applicable

  - **What range of applications is the alternative designed for?** The Alascan literature claims a 12 person maximum for this system. Equaris is currently designing some small cluster systems (personal communication, Clint Elston, Equaris Corp. 2004).

- **Maintenance Requirements**

  - **How often is maintenance required?** For complete water recycle systems, site visits are recommended every 2-3 months, although Equaris does try to train residents so that maintenance visits are minimized. (personal communication, Clint Elston, Equaris Corp. 2004).

  - **How does lack of maintenance affect system performance?** Overflow of solid end product, decrease in treatment performance

  - **What type of maintenance is required? How difficult is it to perform?** Compost is generated at a rate of 5-15 gallons per four-person family per year and must be removed generally on a 1-3 year basis. Other routine maintenance includes changing UV lights in the disinfection system and adding pine mulch to the compost tank (personal communication, Clint Elston, Equaris Corp. 2004). Water quality is continuously monitored via an automated system (water quality data are sent to main office via modem).

  - **Is there a sorptive material to be replaced?** No.

  - **Is there a residual to be disposed of?** Yes

    - **If so, how is it disposed of?** As field fertilizer

    - **How often is this required, and what are the quantities?** Five to 15 gallons compost per four-person family per year.

- **Phosphorus-Recycling Capability**

  - **How available is the phosphorus removed from wastewater for plant uptake?** Not known

- **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** Unlikely; phosphorus comes from feces and urine, which are low in heavy metals.
- **How concentrated is the phosphorus (this affects economic viability of recycling)?** ~19,000 mg P/dry kg

- **Other Treatment Effects**
  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** Unknown
  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** 50-88% TSS removal, 83-90% Kjeldahl Nitrogen, 78-93% BOD, 1000-fold fecal coliform reduction by extended aeration system.
- **Impact on Landscape**
  - **Is the alternative visible or underground?** Visible, in house
  - **If it is visible, what is its appearance?** In-house concrete vault: 146" L × 70" W × 79" H
- **Design**
  - **On what type of sites (soils, etc.) is the technology appropriate to use?** Any indoor location.
  - **Any odor issues to consider in siting the technology?** No.
  - **What are the dimensions (size) of the technology?** 146" L × 70" W × 79" H
  - **How easily can the technology be used in a retrofit situation?** Not known.
  - **Are any changes in user behavior required for this technology to work?** Use of SeaLand or Nepon low-flow toilets.
- **Energy Requirements**
  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.**

Electrical usage is partially flow dependent. A constant usage of ~2000 kWh/yr is required to run the fan, air compressor and UV lights which all are run continuously. Additional electrical usage will be drawn from pumps and will be flow dependent.

- **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** Very little; minimal trucking of waste is required.

- **Cost**

  - **What is the installation cost?** The complete system is $35,000, plus $3,000-5,000 for installation (personal communication, Clint Elston, Equaris Corp. 2004).

  - **What are the operating and maintenance costs?** $400-500 per year (personal communication, Clint Elston, Equaris Corp. 2004).

Urine-Diverting Toilet

Manufacturer: Several. Prominent models with the longest track record are evaluated here.

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☒ Source separation

☐ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

Specially constructed toilets have two bowls, the forward one for urine and the rear one for feces and toilet paper. The urine, containing about 50% of the phosphorus in domestic wastewater, is plumbed to a separate tank. From there, it can be pumped and spread in agriculture as fertilizer.

Technical Description:

The toilets have separate bowls for urine and feces, with a porcelain wall between them. When the user sits on the toilet, urine and feces come out in the direction to fall into the proper bowl. Men can stand or sit when urinating; sitting is more effective in sorting the urine. The urine is flushed with 0.1-0.5 L water per use, and flows to a collection tank, which can be a small septic tank. No ventilation of the pipe system is needed.

The urine is periodically removed from the tank and can be used as fertilizer in agriculture, using the same equipment as for liquid manure. If the urine is to be used in agriculture, storage by itself kills pathogens. Storage can be achieved with two tanks, using the second one while the urine is being stored in the first, or by storing the urine at the farm where it is to be used, for example, in rubber bladders.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☐ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

    - **How long has the phosphorus-removal alternative been used?** Urine diversion has been used for centuries. The units evaluated began being manufactured in the early 1990s.

    - **How many different units have been used?** As of 2000, about 3,000 of the units evaluated had been sold (Johansson 2000).

    - **Under what conditions have they been used?** Individual homes, apartment buildings, schools.

    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** Researchers from a number of Swedish universities and other research institutions have published many papers, reports, and a number of dissertations on the toilets and their use. This evaluation relies primarily on a review of that literature by the Swedish EPA (2002) and a three-year study by Stockholm Water (Hellström *et al.* 2003). (An English-language summary of some of the research as of 2001 is contained in the EcoEng newsletter at http://www.iees.ch/EcoEng011/EcoEng011_F1.html, and a downloadable report in English by Stockholm Water is at http://www.stockholmvatten.se/pdf_arkiv/english/Urinsep_eng.pdf .) Additional experience with the toilet's function is provided by an author (Etnier), who has one installed in his home and who had another installed at his workplace for several years.

- **Phosphorus-Removal Capability**

    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** Full removal of the urine from the wastewater stream would result in about 50% reduction in phosphorus (Vinnerås *et al.* submitted). In practice, depending on how motivated the user is, 65-85% of the urine is successfully separated with these toilets (Jönsson *et al.* 2000; cited in Swedish EPA 2002). From the total wastewater stream, then, 33-43% of phosphorus is removed.

    - **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** P_{tot}

- **How does phosphorus concentration affect removal capability?** The higher the percentage or amount of phosphorus contained in the urine, the higher the potential removal capability. For example, where detergents have low levels of phosphorus or are not used, urine diversion can remove the greatest amount of phosphorus.

- **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** No.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** The amount removed is not affected by variations in flows. Removal would be expected to vary as the percentage of phosphorus in the urine component and the amount of urine in the waste stream vary, perhaps different at schools and restaurants than in homes. Tests have been primarily or exclusively carried out in homes or apartment buildings.

  - **Under what climatic conditions were the tests conducted?** Swedish

  - **How does ambient temperature affect the system?** No effect is expected, except on pathogen removal. See **"Phosphorus-recycling capability,"** below.

  - **What range of applications is the alternative designed for?** Anywhere toilets are regularly used by the same group of people, who quickly become familiar with it. We are not aware of any uses of the toilets as public toilets, and their unfamiliarity might lead to problems.

- **Maintenance Requirements**

  - **How often is maintenance required?** No regular maintenance is required, other than emptying the urine tank when it is full and, if the system is so designed, switching the flow from the first to the second urine tank. Swedish estimates are 365-550 L (100 - 150 gallons) of urine generated per person annually, excluding flush water. For each person home 16 hours/day, the following annual production of urine plus flush water is recommended for dimensioning (Jönsson 2001): for one model, 550 L (150 gal.); for another, 910 L (240 gal.).

  - In addition, the urine trap has been found to clog occasionally (Jönsson 2001). Most of the clogging incidents can easily be remedied with a plumber's snake, while about a quarter of them have required a caustic soda solution. This does not happen often enough that anyone has recommended preventive maintenance.

  - **How does lack of maintenance affect system performance?** Tanks which are not emptied overflow.

- **What type of maintenance is required? How difficult is it to perform?** Emptying tanks; can be done with standard pumping trucks.

- **Is there a sorptive material to be replaced?** No.

- **Is there a residual to be disposed of?** Yes—the urine plus flush water.

    - **If so, how is it disposed of?** May be treated as septage. Because of the reduction in pathogens simply from storage and the low heavy metal content, many people see urine as ideal for use as an agricultural fertilizer.

    - **How often is this required, and what are the quantities?** Depends on the dimensioning of the urine collection tanks and the use. For each person home 16 hours/day, the following dimensioning is recommended (Jönsson 2001): for one model, 550 L (150 gal.); for another, 910 L (240 gal.).

- **Phosphorus-Recycling Capability**

    - **How available is the phosphorus removed from wastewater for plant uptake?** Stockholm Water has experimented with using urine as a fertilizer in small-grain agriculture. When the urine is applied at nitrogen levels (tons/acre) appropriate for the crops, the phosphorus and potassium levels are also appropriate. They found that harvests of grain fertilized with urine have been 80-90% of those fertilized with a roughly equivalent amount of mineral nitrogen fertilizer (Johansson 2000). If ammonia volatilization is accounted for, the yield of urine-fertilized grain is 85-95% of grain fertilized with mineral nitrogen (Johansson 2000).

    - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** Urine is very low in heavy metals, compared to most wastewater sludge. The Stockholm Water study (Hellström *et al.* 2003) found that the content of cadmium, mercury, and lead in urine, per kg phosphorus, was 10% or less of that in composted feces.

      The following table compares Swedish norms (Vinnerås *et al.* submitted) for heavy metals in urine with the levels permitted by the US EPA in EQ (exceptional quality) sludge and the EPA's upper limit on land applied sludge (all numbers are mg/kg):

Table A-5
Heavy Metal Content in Urine Compared With Limits for US EPA's EQ Sludge and EPA's Ceiling for Land-Applied Sludge

Metal	Urine (Swedish Norm)	EPA EQ Sludge	EPA Ceiling Limit
Cd	.37	39	85
Cr	3.7	NA	NA
Cu	37	1500	4300
Hg	1.1	17	57
Ni	2.6	420	420
Pb	0.73	300	840
Zn	16.4	2800	7500

The US EPA also regulates arsenic and molybdenum levels in sludge applied to land (Harrison *et al.* 1999); no figures were found on the levels of these metals in urine.

In short, for all metals in sewage sludge regulated by the US EPA and for which figures on the urine content have been found, the urine is below EQ sludge limits by a factor of more than 10.

Researchers at the Swedish Institute for Infectious Disease Control concluded that six months of storage at 4 °C is sufficient to kill all pathogens, with the possible exception of viruses, and that six months of storage at 20 °C kills all pathogens (Höglund 2001).

While effects of the use of chemotherapy agents and other pharmaceuticals have not been studied sufficiently to know their effects on agriculture, no harmful effects on the fertilized plants have so far been reported from agricultural use of urine.

- **How concentrated is the phosphorus (this affects economic viability of recycling)?** With flush water, 0.7-0.9 g/kg (650 to 850 g/550 to 910 L).

- **Other Treatment Effects**

  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** Eighty percent of the nitrogen from domestic wastewater is also removed with the urine. Because less flush water is used, the remaining water becomes more concentrated in organic matter.

  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in**

BOD, reduction in TSS? Quantify. Eighty percent of the nitrogen is also removed with the urine.

- **Impact on Landscape**
  - **Is the alternative visible or underground?** At least one separate urine tank is needed; it can be underground.
- **Design**
  - **On what type of sites (soils, etc.) is the technology appropriate to use?** All
  - **What are the dimensions (size) of the technology?** The toilet is normal size; the tank can be any size one wishes.
  - **How easily can the technology be used in a retrofit situation?** Separate plumbing is needed for the urine pipes; this may be difficult to install in existing buildings.
  - **Are any changes in user behavior required for this technology to work?** Yes. The toilet is of a different design than most plumbers and users are used to. Surveys have been done of people who have had the toilet in their homes for six months to three years (Johansson 2000). Some early problems were discovered from incorrect installation and corrected, and experience was gained in quickly fixing clogged urine traps, after which users' attitudes improved (Johansson 2000; Swedish EPA 2002). One model was said to be more difficult to keep clean than a conventional toilet, while another was said to be easier to keep clean than a conventional toilet. Some male users had stopped using the front bowl when they stood and urinated. The users' attitudes toward these toilets have been most positive where they have been informed of the environmental benefits of the toilets and given instructions in preventing and fixing any stoppages that occur in the urine pipe.

    More information on user satisfaction is provided from a Danish survey of 81 allotment gardens where users had used various models of urine-diverting, composting toilets (Backlund *et al.* 2003). Unlike the Swedish surveys, the users in Denmark had all volunteered to try out the toilets. People at only two of the allotment gardens reported that the toilets had not satisfactorily sorted the urine and feces. In both cases, most of the urine from the women went into the feces bowl. However, no problems with odor or maintenance of the toilet were reported for one of these facilities, and a small odor problem was reported at the second, where, nonetheless, their overall impression was that the toilet worked excellently. In addition, another 11 users of the toilets reported that the sorting worked imperfectly either for regular female users or female guests. Of the children whose use was reported, 5 of 24 had some difficulties or had problems with using the toilets. In general, users did not think that any difficulties they had with using the toilets were great.

The three users interviewed in Stockholm Water's study (Hellström *et al.* 2003) represent a much smaller sample than in the other studies, but they add different perspectives. One said that women flush the feces bowl as well as the urine bowl to get the toilet paper to go away—clearly pointing to a need for education about either leaving the toilet paper in the feces bowl after each urination or putting toilet paper from urination in a trash can. Another said that more cleaning was needed than with conventional toilets, perhaps because two smaller bowls are more complicated to clean than one big one.

- **Energy Requirements**

    - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** Not applicable.

    - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** Five hundred to one thousand liters of urine and flush water per person are collected annually and trucked to a farm for use as fertilizer.

- **Cost**

    - **What is the installation cost?** A toilet from Sweden, imported into the eastern US, costs about $2,000 with shipping and customs. Installation of the unfamiliar toilet costs somewhat more for a plumber than installation of a conventional toilet. An extra set of pipes and an extra tank are required, adding another $2,000 to the total installation cost.

    - **What are the operating and maintenance costs?** Pumping and transport of urine every six months to three years, depending on use and tank dimensions. With a 1000 gallon tank, a four-person household may require pumping every 1-2 years. If the urine is land applied under a septage permit, the cost would be the same as for the equivalent amount of septage. If special measures are taken to keep the urine from being mixed with septage (to prevent contamination from the pathogens in the septage) during transport, the cost could be greater, unless there are sufficient numbers of the units in use in an area to bring the costs down. Estimated life-cycle costs: $9,200 - $12,000.

Alum Injection

Manufacturer: Generic Technology.

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☒ Septic tank or substitute for septic tank

☐ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

Translated freely from af Petersens (2003): An alum injection system uses chemical precipitation of phosphorus with a conventional septic tank used for sedimentation of both the primary sludge and the chemical sludge. The technology is developed principally as an upgrading of existing wastewater treatment systems with septic tank and SAS, but it can also be used in new construction. Alum injection can be used either for graywater or the complete wastewater stream, and can be used in individual houses as well as apartment complexes or groups of houses.

Technical Description:

An aluminum-based precipitant is dispensed at timed intervals into a wastewater pipe in the house. Phosphorus precipitates out in the wastewater pipes and in the septic tank, and the chemical sludge is collected in the septic tank. The manufacturer says that the flocculant particles also absorb dissolved substances and adsorb suspended solids. After the primary and chemical precipitation in the septic tank, the effluent is to be biologically treated, e.g., in a SAS.

For one model examined in detail, the control unit ($20 \times 25 \times 10$ cm) is made of stainless steel. The chemical container is a 15-liter plastic jug. The timed dosage is programmed into the control unit, based on the size of the family and/or other factors.

This technology could be used in cluster systems if each house has its own septic tank.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☐ Large system, over 3,500 gallons per day

☐ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

    - **How long has the phosphorus-removal alternative been used?** Not fully known. Two units were used in single-family houses in a two-year Swedish study that began in early 2000. The technology has been referred to in publications since at least the 1980s. An article by Brandes (1977) may report the first testing of the method.

    - **How many different units have been used?** Not fully known. Two units were used in single-family houses in a two-year Swedish study that began in early 2000.

    - **Under what conditions have they been used?** Not fully known. Two units were used in single-family houses in a two-year Swedish study that began in early 2000.

    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** Independent data from a third party evaluation by Stockholm Water, the water/wastewater utility for Stockholm, Sweden. Two units were used in single-family houses in Stockholm Water's three-year study just south of Stockholm that began in early 2000.

- **Phosphorus-Removal Capability**

    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** The reporting of the independent test results is somewhat contradictory, saying that 50-90% of total phosphorus was captured in the septic tank one place (p. 120) and 80-90% was captured in another (p. 122) (Hellström *et al.* 2003).

    - **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** Phosphate and P_{tot}

- **How does phosphorus concentration affect removal capability?** Not measured. Incoming concentration estimated, using mass balance calculations.

- **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** No information found.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** Dosage is timed, irrespective of actual wastewater flows. Test data reported on water samples are after the soil absorption system, and they are stable throughout the year, ranging from 0 to 0.4 mg/L. The manufacturer says that the phosphorus removal is less with underdosing (or high water flows) and that the pH level in the septic tank is lowered with overdosing. No pH under 7 was recorded by Hellström *et al.* (2003).

  Brandes (1977) reports flushing alum down a toilet at various concentrations, and phosphorus removal ranges from 75% at around 125 mg alum/L to over 95% at 450 mg/L.

  - **Under what climatic conditions were the tests conducted?** Stockholm: roughly equivalent to Boston in the winter and coastal Maine in the summer.

  - **How does ambient temperature affect the system?** Test data reported on water samples are after the soil absorption system, and they are stable throughout the year, ranging from 0 to 0.4 mg/L. No seasonal variation is shown.

  - **What range of applications is the alternative designed for?** According to af Petersens (2003), it can be placed in a single house, an apartment complex, or a group of houses.

- **Maintenance Requirements**

  - **How often is maintenance required?** The 15-liter precipitation chemical container must be replaced when it is empty. The septic tank must be emptied at least twice a year (p. 124, Hellström *et al.* 2003).

  - **How does lack of maintenance affect system performance?** The phosphorus removal occurs because of the addition of the precipitation chemical. If the container becomes empty and no chemical is added, one would expect the performance to drop, says the manufacturer. However, the performance levels reported here were from two facilities where the chemical dosing was imperfect, either because an empty container was not replaced or because of technical problems with the dosing. If the septic tank is not emptied often enough, there is a risk of solids being transported to the SAS and clogging it.

- **What type of maintenance is required? How difficult is it to perform?** Replacing the chemical container is easy (Hellström *et al.* 2003). Emptying the septic tank is performed by trained professionals with special equipment. The wastewater pipe into which the chemical is added has shown a tendency to get clogged (p. 125, Hellström *et al.* 2003).

- **Is there a sorptive material to be replaced?** No.

- **Is there a residual to be disposed of?** Yes

  - **If so, how is it disposed of?** As with septage.

  - **How often is this required, and what are the quantities?** 2-3 times per year for a 4-5 m^3 (1,100-1,300 gal.) septic tank.

- **Phosphorus-Recycling Capability**

  - **How available is the phosphorus removed from wastewater for plant uptake?** As available as that from wastewater treatment plants, according to the manufacturer. This probably refers to wastewater treatment plants with chemical precipitation.

  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** The manufacturer says that the precipitation chemical is used in drinking water plants, so it is presumably rather clean.

  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** Two septic tank loads per year for 80-90% of one household's phosphorus. Manufacturer recommends a 4-5 m^3 (1,056-1,321 gal.) septic tank so there is enough settling time even for large families with kids who shower a lot.

- **Other Treatment Effects**

  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** Hellström *et al.* (2003) showed that the septic tank sludge contained 10% of tot-N and 50% of the COD of the total of the sludge plus the septic tank effluent (calculated from Hellström *et al.* (2003) Tables 54-55). No tests of tot-N or COD in the septic tank influent were reported, so these numbers represent a minimum reduction.

- **Impact on Landscape**

  - **Is the alternative visible or underground?** The dosing station is placed in the house, and there is great flexibility about where it is located.

- **If it is visible, what is its appearance?** The control unit (20 × 25 × 10 cm) is made of stainless steel. The chemical container is a 15-liter plastic jug.

- **Design**

  - **On what type of sites (soils, etc.) is the technology appropriate to use?** Hellström *et al.* (2003) calculated that the cost in Sweden of installing alum injection plus a soil absorption system is about the same as for a package treatment plant. However, where there is already a septic tank and soil absorption system, alum injection is a more cost-effective way to achieve phosphorus reduction.

  - **Any odor issues to consider in siting the technology?** No information

  - **What are the dimensions (size) of the technology?** The control unit (20 × 32 × 53 × 10 cm) is made of stainless steel. The chemical container is a 15-liter plastic jug.

  - **How easily can the technology be used in a retrofit situation?** It is perhaps most suited for retrofits.

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** Electricity use is 30 kWh/year (Hellström *et al.* 2003) or less than 100 kWh/year (af Petersens 2003). It is not flow dependent.

  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** The 4-5 m^3 septic tank is emptied 2-3 times per year and the septage is hauled to wherever it is hauled in that area.

- **Cost**

  - **What is the installation cost?** In Sweden, 12,500 SEK according to af Petersens (2003). At exchange rate 1 USD = 7.47 SEK (2004.09.17) = $1,673. According to Hellström *et al.* (2003), about 15,000 SEK ($2,008) in Sweden (i.e., without shipping). If shipping is assumed to be similar to that for the Aquatron, and the higher figure is used for the purchase cost but (as a compensation) nothing is added for installation labor, the total installed cost is $2,400.

- **What are the operating and maintenance costs?** Electricity use is reported as 30 kWh/year (Hellström *et al.* 2003) or less than 100 kWh/year (af Petersens 2003) (less than $6.60/year, using average US electricity cost). Chemical use costs are reported as about 1,000 SEK/year (Hellström *et al.* 2003) or 2,000 - 4,000 SEK/year plus shipping (af Petersens 2003). Assuming 4,000 SEK for chemical costs, they are $535/year. Because of the extra sludge produced, the septic tank needs to be emptied 2-3 times a year. The present value of O&M, assuming 2.5 tank pumpouts per year, is $32,000, for an estimate life-cycle cost of $34,000.

RUCK CFT

Manufacturer: Holmes and McGrath, Inc.
www.holmesandmcgrath.com
Phone: (508) 548-3564
Fax: (508) 548- 9672

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☒ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

The RUCK CFT system is an add-on to a traditional onsite treatment system, located between the septic tank and soil absorption system (see Figure A-2 and Figure A-3 at the end of this form). The original RUCK designed is described by Laak (1988). The RUCK CFT system was designed primarily for nitrogen removal in nitrogen-sensitive areas; however, phosphorus removal as high as 90% has been observed in systems for which data are available. The major components of the RUCK CFT systems are a septic tank, the RUCK filter, and a mixing chamber/second septic tank, followed by effluent dispersal. The RUCK filter consists of alternating layers of a fine mason sand and double-washed 3/4" stone, and is vented in order to stay aerobic. The septic tank effluent is distributed evenly across the filter by perforated PVC laterals, and the effluent is contained in the filter by a landfill liner.

There are currently two different RUCK systems commercially available: the “traditional” RUCK system and the RUCK CFT. The traditional RUCK system is used to treat single homes or sites producing <2000 gal/day of waste and has not been identified as having significant phosphorus-removal capability. The RUCK CFT system is used to treat larger flows, and has been used at sites producing as much as 16,500 gal/day of waste. The traditional and CFT systems differ only in the size of the components and in the composition of the “graywater.” In the traditional RUCK systems that are currently being installed, all household wastes are designed to flow through the RUCK filter with the exception of the laundry discharge. The laundry discharge is diverted to the mixing chamber/second septic tank to serve as a carbon source for anaerobic denitrification. The RUCK CFT system differs slightly from the traditional system in that all waste streams are sent through the RUCK filter and an external carbon source (soap) is added to the system in the mixing chamber.

The RUCK system has been has been used since 1977, and it has received multiple system alterations. Most of these changes involved altering the “graywater” or carbon source composition. This evaluation reflects the RUCK CFT system, available since 2002.

Technical Description:

In the RUCK CFT, nitrogen removal is achieved via aerobic nitrification followed by anaerobic denitrification. The aerobic nitrification reaction occurs in the RUCK filter. Following the RUCK filter, the effluent passes into an anaerobic zone in the mixing chamber/second septic tank. The addition of a carbon source (soap) to the anaerobic chamber promotes denitrification. Phosphorus removal has also been observed in the system; however, the mechanism for removal is not entirely known. Data from the RUCK CFT systems suggests that the majority of phosphorus removal occurs in the RUCK filter, and is hypothesized to be either from absorption or sedimentation in the sand filter. This process is believed to be enhanced by low pH (<5) after nitrification, according to the manufacturer.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

    - **How long has the phosphorus-removal alternative been used?** RUCK systems have been used since 1977; however, the system components have changed slightly over this time (primarily the carbon source). The current RUCK CFT systems date to 2002 (Laak 1995; personal communication, Timothy Santos, Holmes and McGrath 2004).

    - **How many different units have been used?** More than 200 RUCK systems since 1997. Four of these were RUCK CFT systems (Laak 1995; personal communication, Timothy Santos, Holmes and McGrath 2004).

- **Under what conditions have they been used?** RUCK systems have been used from California, Vermont, and Maine to southern New Jersey (Laak 1995). The RUCK CFT system has only been installed in Massachusetts thus far. Optimal operating temperature for microbial nitrification in the RUCK filter is 30 °C.

- **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** A small amount of data are available for phosphorus removal by the RUCK systems. The best data available is from two RUCK CFT systems (2-4 years in duration) installed in Massachusetts by Holmes and McGrath. These results were prepared by Holmes and McGrath for the Massachusetts State Department of Environmental Protection. No phosphorus-removal data are currently available for the smaller "traditional" RUCK systems that have been installed by Holmes and McGrath, as the state environmental departments have not required phosphorus testing. Some data on phosphorus removal by older systems are provided by Laak (1995); however, these systems differ from the current RUCK systems in the composition of the graywater, or carbon source.

- **Phosphorus-Removal Capability**

  - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** In the older technology, in which the kitchen sink effluent is included in the graywater, ~65% phosphorus removal can be expected (Laak 1995). By converting the kitchen sink to the blackwater side, higher phosphorus removal is expected, however, no data to support this hypothesis are available (personal communication, Timothy Santos, Holmes and McGrath 2004). In the RUCK CFT systems, phosphorus removal in the RUCK filter effluent was as high as 90%. This level of removal efficiency was consistent at the Lunenburg, Massachusetts site; however, at the Falmouth, Massachusetts site, two distinct dips in removal efficiency (down as low as 30%) were observed. These dips in removal efficiency are speculated to be a result of high phosphorus levels in the waste stream at those times (personal communication, Timothy Santos, Holmes and McGrath 2004).

  - **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** P_{tot}

  - **How does phosphorus concentration affect removal capability?** No conclusive studies are available on the effect of phosphorus concentration on removal efficiency, however, from the RUCK CFT data at Falmouth Massachusetts, a decrease in removal efficiency was observed, potentially from high phosphorus concentrations in the waste stream. More data are needed to understand this relationship better.

  - **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** The pH needs to be low (<5) for the silica-phosphorus complexes to form in the RUCK filter, according to the manufacturer. Long-time onsite system researcher James Converse reports (personal communication) that tests of 50 sand filters by the University of Wisconsin–Madison found an average pH of 7, so it is not clear how often the low pH requirements will be met. Nitrification releases carbonic acid and consumes alkalinity, but it takes place optimally at pH 6.5-8 and in low-alkalinity waters it may be inhibited by the lack of alkalinity (Oakley 2003).

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** No studies available. The traditional RUCK systems are designed for flows <2000 gal/day. The RUCK CFT systems were receiving flows between 12,500 and 16,500 gal/day (personal communication, Timothy Santos, Holmes and McGrath 2004); however, no data are available as to how fluctuations in flow will affect the system.

  - **Under what climatic conditions were the tests conducted?** The traditional systems have been used in a variety of locations in the United States (Maine, Vermont, California, New Jersey). The CFT systems have only been used in Massachusetts thus far.

  - **How does ambient temperature affect the system?** Microbial degradation is optimized at 30 °C. However, the system has proven effective at lower temperatures, such as in the northeast United States.

  - **What range of applications is the alternative designed for?** As described above.

- **Maintenance Requirements**

  - **How often is maintenance required?** According to Laak (1995), sand filter has the capacity to complex phosphorus for several hundreds of years of typical phosphorus output from human urine. No information however, is given on how this estimation was made. No long-term data exist for phosphorus removal by either of the RUCK systems.

    In the traditional RUCK systems, blackwater septic tank requires pumping approx. every 4 years, graywater every 10 years or more (Laak 1995). Holmes and McGrath currently visits each of the traditional RUCK systems once a year, as required by the state, for routine monitoring (personal communication, Timothy Santos, Holmes and McGrath 2004). None of the RUCK systems have needed the RUCK filter to be replaced in over 24 years of operation. The RUCK CFT systems are monitored once a week as required by the state. Little maintenance is required other then periodic pumping of the septic tanks and refilling the container which holds the carbon source. The largest CFT systems may go through a 55 gal drum of soap (as a carbon source) in a one-week period (personal communication, Timothy Santos, Holmes and McGrath 2004)

    How does lack of maintenance affect system performance? System will back up if septic tanks are not pumped. Similar to traditional septic system.

- **What type of maintenance is required? How difficult is it to perform?** Septic pumping, same as traditional septic system
- **Is there a sorptive material to be replaced?** Only if the RUCK filter needs to be replaced, this occurs infrequently.
- **Is there a residual to be disposed of?** Similar to standard septic tank, frequency of removal depends on the amount of waste being generated.

- **Phosphorus-Recycling Capability**
  - **How available is the phosphorus removed from wastewater for plant uptake?**
  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** Laak (1995)found the septage from the blackwater tank to be ~20% phosphorus. In the current systems, phosphorus concentrations in the septage are expected to be similar to that of a standard septic tank. No data are available for phosphorus concentrations in spent RUCK filters (none have been replaced).

- **Other Treatment Effects**
  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** Removal of nitrogen via denitrification, BOD and TSS in the RUCK filter can be expected. Typical numbers include <3mg/L TN; <5mg/L BOD; <5mg/L TSS (Laak 1995).

- **Impact on Landscape**
  - **Is the alternative visible or underground?** Primarily underground with air vent protruding from the RUCK filter
  - **If it is visible, what is its appearance?** Single vent pipe

- **Design**
  - **On what type of sites (soils, etc.) is the technology appropriate to use?** The leach area is under the same state-mandated constraints as that of a SAS used in conjunction with a typical septic system (personal communication, Timothy Santos, Holmes and McGrath 2004).
  - **Any odor issues to consider in siting the technology?** No.
  - **What are the dimensions (size) of the technology?** Total land area used for a single house design is 280 ft^2 (Laak 1995). This area can be divided into fractional areas (does not have to fit into one square location).

- **How easily can the technology be used in a retrofit situation?** Unknown

- **Are any changes in user behavior required for this technology to work?** No, except with the addition of soap to the system as a carbon source. This, however, is usually performed by a technician.

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** None in the traditional RUCK system if no lift station is used. If a lift station is necessary, an electric pump may use up to 90 kWh/yr. In the RUCK CFT system, a small pump is used to move the carbon source to the mixing chamber.

  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** The traditionally designed septic tank will be emptied when full and the septage is hauled by truck to a wastewater treatment plant. Frequency of pumping depends on the size of the wastewater discharge.

- **Cost**

  - **What is the installation cost?** For the traditional RUCK system, $10,000 in addition to the cost of a septic tank and SAS (personal communication, Timothy Santos, Holmes and McGrath 2004). In the RUCK CFT system, the RUCK components alone (excluding the soil absorption system, septic tank, piping network, etc.) are installed at a price of $25 per gallon of water treated per day (personal communication, Timothy Santos, Holmes and McGrath 2004). This would equate to a total cost of around $412,500 for the RUCK CFT system installed in Falmouth, Massachusetts and $312,500 for the RUCK CFT system installed in Lunenburg, Massachusetts.

  - **What are the operating and maintenance costs?** With twice-yearly inspections and replacing the filter medium every ten years, operation and maintenance costs over 30-year life cycle are estimated to be $15,000 more than conventional septic system. The RUCK CFT system will most likely have required state monitoring of water quality, as well as the costs of periodic septic pumping and refilling of the soap (carbon source) reservoir. The total life-cycle costs are, therefore, $25,000.

Schematics for the traditional RUCK and RUCK CFT systems are shown in Figure A-2 and Figure A-3.

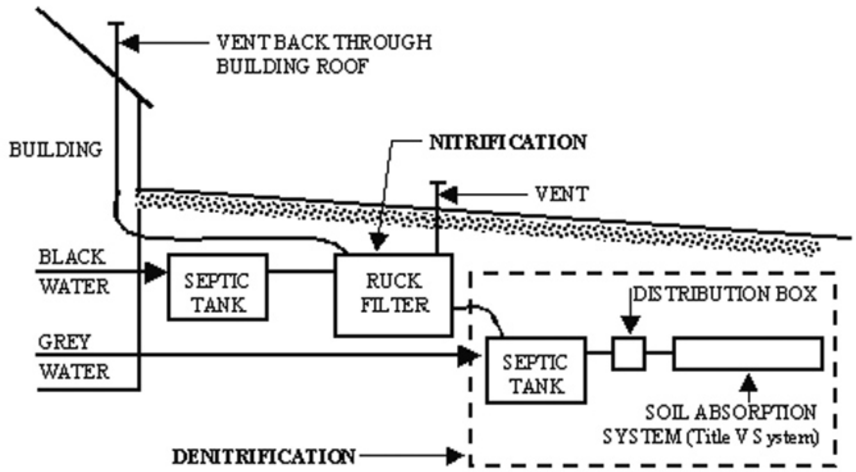


Figure A-2
Traditional RUCK

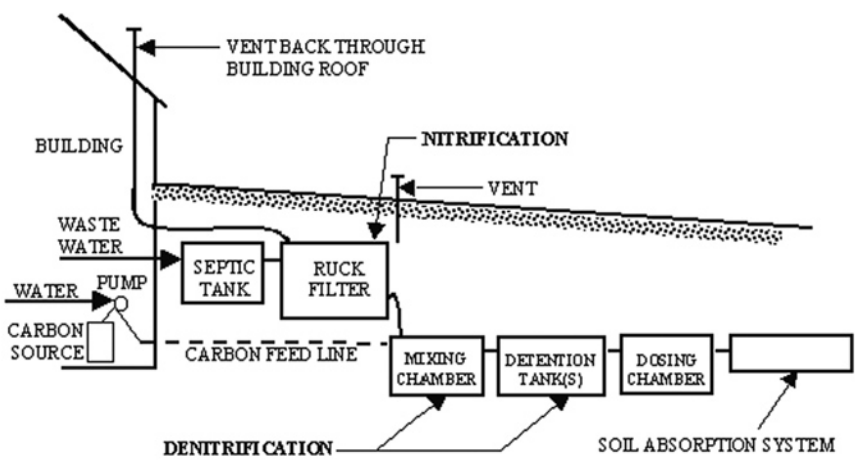


Figure A-3
RUCK CFT

Lightweight Aggregates for a Packed-Bed Filter

Manufacturer: **Generic Technology**

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☒ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

Lightweight aggregates (LWAs) are a sort of clay “popcorn” with high surface area and are often used in horticulture. Some are specially manufactured to increase their phosphorus-sorption capability. It can be used as a medium in packed-bed filters of various designs.

Technical Description:

Filtralite is an expanded clay aggregate, a sort of clay “popcorn” with high surface area and are often used in horticulture. Filtralite is specially manufactured to increase its phosphorus-sorption capability. It can be used as a medium in packed-bed filters of various designs. One type is composed of 62% SiO_2, 18% Al_2O_3, 7% FeO_3, and less than 5% each of K_2O, MgO, CaO, and Na_2O.

Norway has experimented with many lightweight aggregates (e.g., Zhu *et al.* 1997). The Norwegian treatment facilities built with LWAs have consisted of a vertical-flow packed-bed filter followed by a horizontal-flow constructed wetland system containing Leca. The wetlands have been vegetated or unvegetated; no difference in treatment performance was detected (Jenssen *et al.* 2004). The US tests in the Florida Keys have used drip irrigation on a vertical-flow packed-bed filter.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

  - **How long has the phosphorus-removal alternative been used?** Has been used for phosphorus removal in onsite wastewater treatment plants since the early 1990s. One manufacturer reports that their product "has been used as a biofilm carrier in filter tanks for decades."

  - **How many different units have been used?** One manufacturer's web site lists 88 sites where their product is used in wastewater applications, with phosphorus removal a part of almost all of them.

  - **Under what conditions have they been used?** For domestic and commercial wastewater treatment.

  - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** Numerous articles and dissertations, primarily from the Agricultural University of Norway. The manufacturer has funded some of this research, but the researchers have had full control over publication of results.

- **Phosphorus-Removal Capability**

  - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** For 12 constructed wetland systems using LWAs, average removal is 79%-98% (Jenssen *et al.* 2004). Over time, the manufacturer has changed the "recipe" to increase the phosphorus-removal capabilities. Removal percentage is over 95% in all 10 facilities that use blackwater, and they are built from 1991 to 2000. Effluent phosphorus concentrations range from 0.05 to 0.6 mg/L.

Removal is 79% and 89% in the two facilities using graywater, which has an influent P_{tot} of less than 1.0 mg/L. However, we do not have dimensioning information on all the facilities; it may be that the lower removal percentage in the graywater treatment facilities is due to the dimensioning rather than the lower concentration of phosphorus in the influent.

A study in the Florida Keys study found that the LWA tested in phase II had the highest phosphorus removal of any method tested, averaging 94% with a mean effluent concentration of 0.53 mg/L (Ayres Associates 2000).

- **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** P_{tot}
- **How does phosphorus concentration affect removal capability?** See "what affects the range", above.
- **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** No information.

- **Robustness of the System**
  - **How is the system's performance affected by variations in flows and in wastewater composition?** We have no direct information on that. Some of the Norwegian facilities using LWAs are institutions which have strong variations in wastewater flows, e.g., a school and university dormitory. Their reported removal is all 89% or greater. However, we do not have enough information on the sampling routines to know whether they were likely to capture variations in removal with variations in flow.
  - **Under what climatic conditions were the tests conducted?** The Norwegian facilities are in southern Norway, where the climate is similar to Boston's in the winter and coastal Maine's in the summer. The Florida Keys experiments were conducted in a sub-tropical marine climate.
  - **How does ambient temperature affect the system?** In the Norwegian facility for a university dormitory, the septic tank effluent temperature during the winter ranged from 10 to 15 °C and the temperature dropped only 2-3 °C as the effluent passed through the treatment facility (Gulbrandsen 1999; as cited in Jenssen and Vråle 2004).
  - **What range of applications is the alternative designed for?** Any type of septic tank effluent that might be treated in a packed-bed filter.

- **Maintenance Requirements**
  - **How often is maintenance required?** Jenssen *et al.* (2004) suggests that subsurface-flow constructed wetlands can be designed to provide >90% phosphorus removal for

15 years (no dimensions given). Systems using earlier versions of Filtralite (Leca) have been operating with continued high removal rates since the early 1990s. Filtralite-P sorption capacity is given as 12 g/kg in Jenssen *et al.* (2004).

- **How does lack of maintenance affect system performance?** No further removal of phosphorus expected after the sorption capacity of the filtrate is met.

- **What type of maintenance is required? How difficult is it to perform?** Replacement of medium when saturated. The material is light enough that it can be removed by a septage pumper truck.

- **Is there a sorptive material to be replaced?** Yes

    - **If so, how often does this need to be done?** Every 15 years or so, under Norwegian dimensioning guidelines.

    - **What are the costs and operations performed when it is replaced?** No information found.

- **Is there a residual to be disposed of?** No.

- **Phosphorus-Recycling Capability**

    - **How available is the phosphorus removed from wastewater for plant uptake?** The saturated medium can be used as a fertilizer (Jenssen *et al.* 2004)

    - **How concentrated is the phosphorus (this affects economic viability of recycling)?** No information

- **Other Treatment Effects**

    - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** With at least one LWA, the pH is high (12 or so).

    - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** According to Jenssen *et al.* (2004), in subsurface-flow constructed wetlands using similar material, 40-60% nitrogen removal was achieved as well as <1000 thermotolerant coliforms per 100 ml in system effluent

- **Impact on Landscape**

    - **Is the alternative visible or underground?** Typically used in subsurface-flow constructed wetlands

  - **If it is visible, what is its appearance?** Bare LWA may be on the surface, or it may be vegetated.

- **Design**

  - **On what type of sites (soils, etc.) is the technology appropriate to use?** Soil type does not affect system performance.

  - **Any odor issues to consider in siting the technology?** No published information. None observed in those we have personal experience with.

  - **What are the dimensions (size) of the technology?** Biofilter/Constructed wetland systems described in Jenssen *et al.* (2004) and Jenssen and Vråle (2003)) were designed to cover surface area of 1-3 m^2/person and 1-2 m^2/person, respectively. Design will be based on sorption capacity of filter media, which is given as 12 g P/kg LWA for one type (Jenssen *et al.* 2004).

  - **How easily can the technology be used in a retrofit situation?** No information

  - **Are any changes in user behavior required for this technology to work?** No.

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** None, with the possible exception of a pump to increase flow rate.

  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** No information.

- **Cost**
  - **What is the installation cost?** Cost dependent on design; expected to be more expensive than a typical sand filter. Construction and installation costs estimated to be $8,600 more than conventional septic system, for the bed size constructed in the Florida Keys test (Ayres Associates 1998).
  - **What are the operating and maintenance costs?** Operation and maintenance costs over 30-year life cycle are estimated to be $17,000 more than conventional septic system, based on replacement of the medium every 10 years (Ayres Associates 2000), inspections twice a year, and pump replacement every 8 years (Hoover 1997). This gives a total estimate life-cycle cost of $25,000 over that of a conventional system.

Basic Oxygen Furnace Slag in Packed-Bed Filters

Manufacturer: Generic technology

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☒ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

A packed-bed filter is placed in the treatment train after the septic tank and aerobic treatment. No sludge is produced; phosphate precipitates on the outside of the medium. The medium is expected to become saturated with phosphorus eventually, so medium replacement needs to be part of long-term maintenance. The effluent from the packed-bed filter has a high pH (10-12), so some method of neutralizing the effluent may be required before dispersal.

Technical Description:

One type examined in detail contains a mixture of fine (<25mm) oxides of iron and calcium and coarse materials (0.5 - 5.0 mm) consisting of sand or sand and limestone. The fine particles are enough to substantially coat the coarse particle, but no more than 20% of the total weight of the medium, so as to not clog the interstices. The fine particles can be derived from the waste of a steel manufacturing process.

The phosphates in the effluent react with the fine metal oxides on the surface of the coarse particles to form calcium and iron phosphates. The metal oxides also catalyze the conversion of organic phosphorus to orthophosphate, allowing the removal of organic phosphorus in about the same residence time as that needed to remove incoming orthophosphate.

Because of the high effluent pH, neutralization of the effluent is probably desirable. One vendor recommends a peat filter for uses with small to medium flows and suggests other methods, like addition of carbon dioxide, for larger flows.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**
    - **How long has the phosphorus-removal alternative been used?** Since at least 1999.
    - **How many different units have been used?** At least three are known about.
    - **Under what conditions have they been used?** Massachusetts, Ontario, and Georgia.
    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** All data have been provided to Stone Environmental by a US vendor. Some were from installations at a third-party test site, before the test site staff had completed quality control. The data collected in Ontario was also collected by a third party, according to the US vendor.
- **Phosphorus-Removal Capability**
    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** At the third-party test site, > 97% total phosphorus was removed from an inlet concentration of around 4 mg/L (effluent total phosphorus of 0.1 mg/L). At the Ontario site, 99% removal of total phosphorus was achieved from an influent concentration of around 10 mg/L (Lombardo 2003).
    - **How does phosphorus concentration affect removal capability?** Not enough data available at this point. As described above, the technology was effective at both 4 and 10 mg/L total phosphorus in influent.
    - **Do other water chemistry factors (e.g., pH, BOD, TSS, NO3-, NH_3^+) affect removal capability?** Pretreatment is required to reduce the organic loading for the

wastewater (Lombardo 2003). No other information available on additional chemical interferences.

- **Robustness of the System**
  - **How is the system's performance affected by variations in flows and in wastewater composition?** Not enough data available at this point.
  - **How does ambient temperature affect the system?** Both of the studies evaluated in Lombardo (2003) were from areas that receive snow and freezing temps in winter.
  - **What range of applications is the alternative designed for?** Currently all applications are being considered
- **Maintenance Requirements**
  - **How often is maintenance required?** Longevity of the medium depends on the influent concentration but is expected by a vendor to last 15-20 years. Neither filter needed maintenance at any time during the length of the studies examined. If a peat filter is used for pH neutralization, however, periodic replacement will be necessary. After less than 2 years of operation in one study, the peat filter was ready to be replaced. More data are needed to better determine the cost effectiveness of using peat filters (Lombardo 2003).
  - **How does lack of maintenance affect system performance?** Although the lifespan of the BOF slag filter medium is long (15-20 years expected), it can be assumed that the removal efficiency of phosphorus will diminish as the reactive sites on the medium become filled. If the peat filter fails, which is likely to occur much more frequently, then highly alkaline waters may occur downgradient from the site.
  - **What type of maintenance is required? How difficult is it to perform?** Replacement of the medium and peat filter. Difficulty unknown
  - **Is there a sorptive material to be replaced?** Yes
    - **If so, how often does this need to be done?** 15-20 years
    - **What are the costs and operations performed when it is replaced?** Unknown
  - **Is there a residual to be disposed of?** No.
- **Phosphorus-Recycling Capability**
  - **How available is the phosphorus removed from wastewater for plant uptake?** No information

- **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** Emissions of cadmium, lead, and mercury are a concern from BOF slag (Treaty signatories 1979). However, Toxicity Characteristic Leaching Procedure (TCLP) tests with a leach solution at pH 2.8 produced leachate from BOF slag without hazardous characteristics (Proctor *et al.* 2000; cited in Smyth *et al.* Undated.)

- **How concentrated is the phosphorus (this affects economic viability of recycling)?** No data available

- **Other Treatment Effects**

  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** Increase in pH, further treatment required in most cases.

  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal?** Reduction of BOD_5 and *E. coli* (Lombardo 2003).

- **Impact on Landscape**

  - **Is the alternative visible or underground?** Underground

  - **If it is visible, what is its appearance?** No information

- **Design**

  - **On what type of sites (soils, etc.) is the technology appropriate to use?** Soil quality does not affect treatment performance.

  - **Any odor issues to consider in siting the technology?** No.

  - **What are the dimensions (size) of the technology?** Unknown

  - **How easily can the technology be used in a retrofit situation?** Fairly easily. It is currently being designed by one vendor as part of a SAS, as separate modular unit located in front of an SAS, and as a permeable treatment wall to intercept a phosphorus-sorption front.

  - **Are any changes in user behavior required for this technology to work?** No

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of**

kWh/year per 100 gallons/day treatment. Specify where the electricity is used. None, unless required in the aeration treatment

- **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** Potentially site visits will be required to replace and haul away existing peat filters every 2 years, and the medium every 15-20 years.

- **Cost**
  - **What is the installation cost?** No information found. Construction and installation costs estimated to be $11,000 more than conventional septic system, based on costs of sand filters.
  - **What are the operating and maintenance costs?** Most significant maintenance cost derives from replacement of peat filter, however, more information is needed on cost. Operation and maintenance costs over 30-year life cycle estimated to be $12,000 more than conventional septic system, based on replacement of the BOF slag every 15 years, replacement of the sand filter medium every 20 years, pump replacement every 8 years, and inspection twice annually (Hoover 1997). The total life-cycle cost is, then, $23,000 over that of a conventional onsite system.

PhosRID™

Manufacturer: Lombardo Associates Inc.
www.lombardoassociates.com
Phone: (617) 964-2924
Fax: (617) 332-5477

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☒ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

The PhosRID™ system is a two-step treatment system, located between the septic tank and SAS, or directly following a primary clarifier in a wastewater treatment plant. More than 90% total phosphorus removal has been observed in the effluent from the PhosRID™ System. Additional removal of nitrogen and BOD gives PhosRID™ an advantage over units that solely remove phosphorus. This system is currently being evaluated by the MASSTC and at a residential site in Georgia by the University of Georgia (Lombardo 2005) and has been approved by the Massachusetts Department of Environmental Protection.

Technical Description:

PhosRID is based on principles described by Robertson (2000): under acid conditions, ferric iron solids release low levels of dissolved ferrous iron, which precipitates phosphorus when oxidized. Dissolved phosphorus is removed from a waste stream through the formation and precipitation of Fe-P complexes in a two-step, redox-driven reaction. In the first step, septic tank effluent is passed through a filter containing a Fe (III) rich soil medium. The reducing capacity of the organic-rich septic effluent causes the reductive dissolution of iron into the effluent stream as ferrous iron. The ferrous iron ion combines with the phosphate ion to form the mineral vivianite in the anaerobic environment. When the liquid is oxidized, such as with a sand filter, the ferrous iron ion is transformed to ferric ion, which reacts with phosphate to form the mineral strengite. In sand filters, the strengite mineral coats the sand particles.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

    - **How long has the phosphorus-removal alternative been used?** Studies at the MSSTC date back to September 2002 (results provided in Lombardo 2003). An additional system was set up at a residential site in Georgia in November 2003; data are not yet available.

    - **How many different units have been used?** Two, with additional research performed at the University of Waterloo.

    - **Under what conditions have they been used?** Massachusetts, Georgia.

    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** All data have been provided to Stone Environmental by Pio Lombardo. Some were from the MASSTC installations, before MASSTC had completed quality control.

- **Phosphorus-Removal Capability**

    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** In the MASSTC study, over an 8 month period, >95% phosphate and 92% total phosphorus was removed from a waste stream initially containing 4.1 mg/L and 5.8 mg/L phosphate and total phosphorus, respectively (Lombardo 2003).

    - **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** Data available for both phosphate and total phosphorus (Lombardo 2003)

    - **How does phosphorus concentration affect removal capability?** More data needed

- **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** More data needed. None detected to date, and none anticipated, according to the manufacturer.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** More data needed. MASSTC studies conducted with flow of 82.5 gal/day.

  - **Under what climatic conditions were the tests conducted?** Massachusetts, Georgia.

  - **How does ambient temperature affect the system?** More data needed

  - **What range of applications is the alternative designed for?** This technology is being considered for a wide variety of applications from single homes to commercial applications. PhosRID™ is considered a total treatment system producing high quality waste (low in BOD, low in nitrogen), rather than a treatment system add-on (Lombardo 2004).

- **Maintenance Requirements**

  - **How often is maintenance required?** Media needs to be replenished – estimated 5 years.

  - **How does lack of maintenance affect system performance?** Unknown (Lombardo 2004)

  - **What type of maintenance is required? How difficult is it to perform?** Periodic replacement of both the Fe (III) rich medium (estimated every five years) and the sand filter (estimated 20 years, as for sand filters in general). The manufacturer says that the iron medium can be removed and replace by a sewage pumper.

    - **Is there a sorptive material to be replaced?** Not a sorptive material—phosphorus is precipitated onto the sand filter medium. The iron medium needs to be replaced every five years, according to the manufacturer, at a cost of $1,500.

  - **Is there a residual to be disposed of?** No, except for sand filter medium at the normal interval for replacing sand filters (estimated 20 years).

- **Phosphorus-Recycling Capability**
  - **How available is the phosphorus removed from wastewater for plant uptake?** No data available.
  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** No
  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** Not known, phosphorus concentration on the sand filter will increase with time.
- **Other Treatment Effects**
  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** None anticipated, according to manufacturer.
  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** 50% reduction in total nitrogen, >95% removal in organic nitrogen, 85% reduction in BOD (Lombardo 2003)
- **Impact on Landscape**
  - **Is the alternative visible or underground?** Underground – not visible
- **Design**
  - **On what type of sites (soils, etc.) is the technology appropriate to use?** Normal soil absorption system design is used. Soil quality does not affect system performance.
  - **Any odor issues to consider in siting the technology?** None, according to manufacturer.
  - **What are the dimensions (size) of the technology?** Approximately 0.75 ft^2 per gallon per day.
  - **How easily can the technology be used in a retrofit situation?** Where there is room, easily.
  - **Are any changes in user behavior required for this technology to work?** No.

- **Energy Requirements**

    - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** One 1/3 horsepower pump – for 20 minutes a day.

    - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** The PhosRID iron medium is removed and replaced every five years.

- **Cost**

    - **What is the installation cost?** Construction and installation costs estimated to be $10,000 more than conventional septic system.

    - **What are the operating and maintenance costs?** Only two systems in place for a few years. Operation and maintenance costs over 30-year life cycle estimated to be $18,000 more than conventional septic system, based on twice-yearly inspections, pump replacement every 8 years, PhosRID medium replacement every 5 years, and sand filter medium replacement every 20 years. If inspections are only made when the PhosRID medium is replaced, the figure drops to $8,000. This gives a total life-cycle cost of $18,000 to $28,000 more than a conventional onsite system.

Peatland™ Sewage Treatment System

Manufacturer: Premier Tech

1, avenue Premier
Rivière-du-Loup (Québec)
G5R 6C1 CANADA
www.premiertech.com
Phone: (418) 867-8883
Fax: (418) 862-6642

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☒ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

Organic materials, such as sphagnum peat moss and lignocellulose, have been incorporated into phosphorus treatment applications. Sphagnum peat moss, more commonly used as a treatment medium in aerobic treatment, has been shown to absorb dissolved phosphorus (Brooks *et al.* 1984; Couillard 1994; Nichols and Boelter 1982), however, the sorption capacity of peat mosses will decrease substantially with time, according to Dennis Martin at Simmering & Associates, a company which formerly manufactured the Peatland system (personal communication, Dennis Martin, Simmering & Associates). Patterson (2004) observed an average phosphorus removal of 75%; however, the system showed a steady decrease in phosphorus removal over an eleven-month period. Different peat mosses may vary greatly in coarseness and surface area, and thus will exhibit a wide range in sorption capacity for phosphorus, according to Martin (personal communication).

Some authors have found a longer-term effectiveness for peat. Nichols and Boelter (1982) report on a facility that was achieving 99% phosphorus removal after eight years, though 45% of that was estimated to be in vegetative uptake and the effluent went through both peat and sand. Both Nichols and Boelter (1982) and Couillard (1994) report on different factors that have been hypothesized to increase phosphorus uptake in peat: presence of aluminum and iron in the peat, and microbial immobilization.

The Peatland system is a combination of sphagnum peat filtration with a subsurface-flow constructed wetland designed to intake septic tank effluent and discharge a high quality waste stream capable of meeting the bacterial standards for swimming (e.g., 77 colony-forming units of *E. coli* per 100 ml). In general, the system is designed to achieve a high level of disinfection, as well as to efficiently remove BOD, TSS and nitrogen for over 20 years. Efficient removal of phosphorus (>80%) has also been demonstrated by the Peatland system during the initial 1-3 years of operation. While the capacity of peat filters to remove phosphorus has been observed to deteriorate much more rapidly than the system's capacity to remove fecal coliforms, BOD, TSS, and nitrogen (personal communication, Dennis Martin, Simmering & Associates; Patterson 2004), Peatland differs significantly from other peat filters. Peatland has sand mixed in with the peat, and the manufacturer says that the sand particle size affects phosphorus removal—finer particles lead to greater phosphorus removal. Peatland also incorporates a wetland after the peat filter, which further increases phosphorus uptake and probably extends the useful lifetime of the system.

Few data on phosphorus removal for longer than 3 years are available, although one data point from a ten-year-old system (without flow rates) showed 90% phosphorus removal. According to Premier Tech, installation costs render the system most suitable for cluster systems of around 5 houses or more.

Technical Description:

The peat filter is comprised of a sphagnum moss and select granular materials, providing a high level of disinfection as well as removal of BOD, TSS, and nitrogen. Downstream from the peat filter is a subsurface wetland containing a porous medium of root systems and granular material, in which further treatment of BOD, TSS, and nitrogen occurs. Phosphorus removal is achieved in both system components, primarily through sedimentation of particulate phosphorus or adsorption of soluble phosphorus onto the granular media.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☐ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☐ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

  - **How long has the phosphorus-removal alternative been used?** The data given by Premier Tech highlight systems that date back to 1999 and were sampled through 2002 (3 years).

  - **How many different units have been used?** Data for phosphorus treatment for a total of four treatment systems, all located in Canada. More than 30 systems are in operation; there are no data for phosphorus removal on these, according to Eric Marcil at Premier Tech (personal communication).

  - **Under what conditions have they been used?** All locations are in Canada for the systems which we have data for.

  - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** The phosphorus removal data are limited to what has been provided by Premier Tech, and only covers two systems that have been monitored for one to three years. The most complete data set is from the Six Nations of the Grand River site, in which three systems were set up at three large schools. Each of the systems was monitored extensively for 8.5 months by Health Canada and an independent consultant, First Nation Engineering Services Limited. One of these systems was then monitored again approximately 3 years after the systems were installed. An additional data set corresponds to a site in North Bay, Ontario and contains data from 23 months of monitoring; however, the party responsible for the monitoring is not named (personal communication, Eric Marcil, Premier Tech).

- **Phosphorus-Removal Capability**

  - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** An average removal of 99.5% total phosphorus was achieved at the three locations in the Six Nations of the Grand River data set during the first 8.5 months of operation. These data do not differentiate between the peat filter effluent and that of the wetland. After 3 years of operation, 89% total phosphorus removal in the Peatland System effluent was achieved at one of these locations; the other two locations were not further monitored. Approximately 82% of the influent phosphorus was removed in the peat filter at this location.

  - At the North Bay site, total phosphorus in the effluent from the Peatland system ranged from 0.18-6.3 mg/L (1.0 mg/L on average), while influent phosphorus concentration ranged from 3-15 mg/L (5.8 mg/L on average). In this data, effluent from the peat filter component ranged greatly from 0.5-15 mg/L (6.3 mg/L on average), suggesting that much of the phosphorus removal occurred in the wetland component of the system and not in the peat filter (personal communication, Eric Marcil, Premier Tech).

- **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** P_{tot}

- **How does phosphorus concentration affect removal capability?** Not enough data given. Influent phosphorus concentrations in both studies ranged from 3-15 mg/L (personal communication, Eric Marcil, Premier Tech), which is typical for septic tank effluent. The manufacturer believes that an increase of the phosphorus concentration will not affect the concentration at the outlet, only reduce the lifespan of the system.

- **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability? Not known.** The manufacturer says that phosphorus removal can be increased by using a finer granular medium (sand) in the peat filter.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** High phosphorus concentrations will likely limit the lifespan of the peat filter. The manufacturer reports that 1.5 times design flow has been observed in the past "without major effects" on performance.

  - **Under what climatic conditions were the tests conducted?** Those typical of central Canada.

  - **How does ambient temperature affect the system?** All tests conducted in cold climate conditions. The manufacturer does not expect any effects of increased temperature on phosphorus removal.

  - **What range of applications is the alternative designed for?** From single home to larger cluster systems or even school-size locations, 2,000 to 30,000 gallons per day.

- **Maintenance Requirements**

  - **How often is maintenance required?** Unknown in terms of phosphorus removal. Systems are designed to achieve a high level of disinfection for over 20 years; however, no data on phosphorus treatment for more than 3 years are available. It is expected that the capacity of the system to remove phosphorus will deteriorate more quickly than the capability of the system to treat and disinfect (personal communication, Eric Marcil, Premier Tech).

  - **How does lack of maintenance affect system performance?** System will become saturated with phosphorus, no removal can be expected beyond saturation (personal communication, Eric Marcil, Premier Tech).

  - **What type of maintenance is required? How difficult is it to perform?** Replacement of the peat filter and replacement of the granular materials in the wetland. It is most likely not cost effective to replace materials simply to achieve better phosphorus-removal capacity.

- **Is there a sorptive material to be replaced?** Yes

  - **If so, how often does this need to be done?** Unknown, more research necessary to determine the longevity of phosphorus removal

  - **What are the costs and operations performed when it is replaced?** Unknown

- **Is there a residual to be disposed of?** No.

- **Phosphorus-Recycling Capability**

  - **How available is the phosphorus removed from wastewater for plant uptake?** Unknown

  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** No

  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** Unknown

- **Other Treatment Effects**

  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** The manufacturer says that pH decreases in the peat filter and increases in the wetland. One test site for which data are supplied shows this occurring, while another shows the pH increase in the wetland does not bring the final effluent pH to that of the incoming wastewater.

  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** Percent removal of fecal coliforms, BOD_5, TSS, NH_4, and TKN were all between 95 and 100% during the 3 years of operation in the Six Nations of the Grand River data set (personal communication, Eric Marcil, Premier Tech). Similar results were obtained in a single test of a ten-year-old facility.

- **Impact on Landscape**

  - **Is the alternative visible or underground?** Underground

- **Design**

  - **On what type of sites (soils, etc.) is the technology appropriate to use?** The system is typically designed for sites that are not capable of receiving septic effluent discharges. The Peatland system is typically designed for surface discharge, thus, site soil characteristics are not of concern, according to Dennis Martin at Simmering & Associates, which formerly manufactured Peatland (personal communication; confirmed by personal communication, Eric Marcil, Premier Tech).

  - **Any odor issues to consider with the technology?** No.

  - **What are the dimensions (size) of the technology?** The peat filter is sized at 1 gal/ft^2/day and the wetland is sized at 2 gal/ft^2/day.

  - **How easily can the technology be used in a retrofit situation?** As long as there is enough area available.

  - **Are any changes in user behavior required for this technology to work?** No.

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** No electric usage

  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flowing dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** Peat filter must be replaced every 20 years, according to the manufacturer. (Replacement every five years is assumed for peat filters by Hoover (1997) and was confirmed with an installer for this project's cost calculations. Note that the design loading rate given for another popular peat filter is almost five times higher than the one given for Peatland.)

- **Cost**
  - **What is the installation cost?** $40,000 for a unit that treats 3,200 gal/day. $80,000 for a unit that treats 7,400 gal/day. These costs include the peat, the control panel, the distribution network, and the technical support on the field during installation. It does not, however, include the installation costs and the transportation fees. Construction and installation costs estimated to be $10,000 more than conventional septic system.
  - **What are the operating and maintenance costs?** With twice-yearly inspections and peat replacement every five years, operation and maintenance costs over a 30-year life cycle are estimated to be $17,000 more than a conventional septic system. The manufacturer expects the peat to last around 20 years, and this is reasonable, considering that the design loading rate for Peatland is about one fifth that of another popular peat filter. The manufacturer also expects an inspection to be necessary no more than once a year. Given these assumptions, plus replacing the pump every eight years, the O&M costs over 30 years drop to $13,000 above those of a conventional septic system.

Nanoparticle Selective Resin

Manufacturer: Several

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☒ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

The iron-based nanoparticle selective resin investigated in detail has been sold as an arsenic removal product for a range of applications ranging from under-the-sink filters to municipal wastewater systems. The manufacturer claims the product has a high capacity for arsenic, vanadium, uranium, and phosphate and can be regenerated using a 2% NaCl, 2%NaOH solution. A system was built in Florida which uses the iron-based resin to remove phosphorus from an agricultural waste stream containing 30-40 mg/L total phosphorus. This treatment system consists of two 4-cubic foot treatment chambers filled with the resin, capable of treating 20 gallons per minute each that are used in conjunction with a chemical flocculation step. Regeneration of the resin is controlled via an automated system and occurs after 50,000 gallons have been treated or no longer than 7 days of operation. The regenerant is placed back into the treatment train before the chemical flocculation (it can be reused four times before the salt level get too high) and the solid residual flocculent is used as an agricultural fertilizer. This system has been running full-scale since approximately April 2004, and it reduced phosphorus levels in the effluent to below 0.5 mg/L. A full-scale evaluation of the system, however, will not be released by the evaluating party until after one year of operation.

Technical Description:

The resin contains spherical particles, 300-1200 microns in diameter, suspended in an organic-based matrix. The organic matrix remains rigid in wet environments, allowing the composition to remain firm for large-scale applications. Information on the specific composition of the spherical particles or the removal process for phosphorus is not given in detail by the manufacturer. It is known that the particles are polystyrene based with an iron oxide-containing functional group.

Phosphate or other dissolved anions bind to the iron-oxide functional group and then are released when in the presence of high pH, high ionic-strength solutions, such as the 2% NaCl, 2% NaOH solution used for regeneration. Phosphate recovery from the regenerant using a chemical flocculent can be used to create a slow-release fertilizer such as magnesium ammonium phosphate or magnesium potassium phosphate.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☒ Large system, over 3,500 gallons per day

☒ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**
  - **How long has the phosphorus-removal alternative been used?** One system has been designed for phosphorus removal and has been operating since April 2004, according to Brian Roy of Royal Consulting Services, who has worked with the system (personal communication).
  - **How many different units have been used?** 1
  - **Under what conditions have they been used?** Florida
  - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** The system in operation was designed and operated by a firm producing data for a Congressional grant that has been administrated through the Natural Resources Conservation Service (NRCS). The data for this evaluation were collected by an independent party (Short Environmental Lab); however, no data will be released until the system has been in operation for one year (personal communication, Brian Roy, Royal Consulting Services).

- **Phosphorus-Removal Capability**
  - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** During the 3 months of operation, effluent phosphorus from the system has been

consistently below 0.5 mg/L from the agricultural waste stream's inlet concentration of 30-40 mg/L (personal communication, Brian Roy, Royal Consulting Services).

- **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** Unknown

- **How does phosphorus concentration affect removal capability?** Largely unknown, the system in use has an inlet phosphorus concentration of 2-10 times that of residential wastewater.

- **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** The manufacturer reports that increases in pH reduce resin loading and that the other factors are not believed to affect the resin.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** Largely unknown; the system in use has an inlet phosphorus concentration of 2-10 times that of residential wastewater, and is treating 40 gal/min, or 57,600 gal/day (personal communication, Brian Roy, Royal Consulting Services).

  - **Under what climatic conditions were the tests conducted?** Florida

  - **How does ambient temperature affect the system?** Not tested

  - **What range of applications is the alternative designed for?** The resin has been used for a wide range of applications for arsenic removal, from under-the-sink cartridges to large-scale treatment plants.

- **Maintenance Requirements**

  - **How often is maintenance required?** In the one system in use, regeneration is performed every 50,000 gallons, or every 7 days (whichever comes first) using a 2% NaOH solution (personal communication, Brian Roy, Royal Consulting Services).

  - **How does lack of maintenance affect system performance?** System will become saturated and no longer remove phosphorus from the waste stream if regeneration does not occur on time.

  - **What type of maintenance is required? How difficult is it to perform?** The regeneration procedure is an automated system and needs to be designed and installed by a engineering/consulting firm. According to Roy (personal communication), it was not simple to get the system running, and few experts in the field exist.

  - **Is there a sorptive material to be replaced?** No, it can be regenerated

- **Is there a residual to be disposed of?** Yes, the regenerant
  - **If so, how is it disposed of?** Phosphorus can be precipitated out of the regenerant using a chemical flocculant and used as a fertilizer.
  - **How often is this required, and what are the quantities?** Once a week, or every 50,000 gallons, for one technology. The quantity is six times the resin volume.

- **Phosphorus-Recycling Capability**
  - **How available is the phosphorus removed from wastewater for plant uptake?** The phosphorus can be precipitated out of the regenerant using a chemical flocculent to create a fertilizer. In the system in Florida, ferric sulfate is added to the system and the precipitate is dried and applied to agricultural fields.
  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** No, as long as the treated effluent does not contain significant quantities of the heavy metals.
  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** In one system, about 135 times the influent P concentration, or 4700 ppm. The concentration is affected by the ratio of the volume treated to regenerant.

- **Other Treatment Effects**
  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** None expected, says the manufacturer.
  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** Removal of arsenic

- **Impact on Landscape**
  - **Is the alternative visible or underground?**

- **Design**
  - **On what type of sites (soils, etc.) is the technology appropriate to use?** Site soil does not effect system
  - **Any odor issues to consider in siting the technology?** No.

- **What are the dimensions (size) of the technology?** The one system currently in use, designed to treat 40 gal/min, consists of two cylinder-shaped chambers, 18 inches in diameter by 6 ft high, or approximately 4 cubic ft in volume (personal communication, Brian Roy, Royal Consulting Services).

- **How easily can the technology be used in a retrofit situation?** Unknown

- **Are any changes in user behavior required for this technology to work?** No, although the operator of one technology must be trained and licensed to handle caustic chemicals. This makes the technology most suitable for cluster systems.

- **Energy Requirements**

  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** Minimal: the system requires a pump and controls for the automated system.

  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** Zero

- **Cost**

  - **What is the installation cost?** It's hard to say for a system at this stage of development. The total cost of the system in Florida for agricultural wastewater exceeds $12,600; however, smaller systems would presumably be needed to treat residential waste from single-family homes.

  - **What are the operating and maintenance costs?** Unknown

Extended Aeration Activated Sludge

Manufacturer: Generic technology

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☒ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

Detailed evaluation of a package treatment plant with mechanical, biological, and chemical treatment that is designed for a single household. The biological treatment is a continuous process in a submerged, suspended packed-bed filter. The treatment plant is preceded by a septic tank.

Technical Description:

Septic tank effluent flows to the unit, where it first undergoes three biological steps (manufacturer's website; af Petersens 2003; Hellström *et al.* 2003). In all of the biological steps, the chambers are filled with polyethylene cones, about 3 cm high and 3.5 cm in diameter, which have a surface area of 330 m^2/m^3. In the first step, without aeration, nitrate in recirculated effluent is converted to nitrogen gas. In the second step, air is blown in for aerobic breakdown of organic matter. The third step, also with aeration, is designed for nitrification of ammonia. Part of the effluent is then recirculated to the first biological step, and part continues to a dosing chamber for the chemical precipitant. (No information was found on what chemical is used.) A final chamber is the settling chamber for the phosphorus sludge.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☐ Cluster system

☐ Large system, over 3,500 gallons per day

☐ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

    - **How long has the phosphorus-removal alternative been used?** The unit investigated has been around since at least the competition for inclusion in that research, which occurred in the winter of 1998/1999.

    - **How many different units have been used?** Thousands of units of the technology in general. Of the one investigated in detail, 67 units had been installed in Sweden as of February 2002 (af Petersens 2003).

    - **Under what conditions have they been used?** Swedish single-family homes, especially in the southern part of the country.

    - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** Independent data from a third party evaluation. Two units were used in single-family houses in this three-year study just south of Stockholm that began in early 2000. Also independently evaluated by the Fastighetskontor (Real Estate Administration) of the municipality of Västerås, according to af Petersens (2003). It’s not clear that af Petersens used the Västerås data; we have not seen them.

- **Phosphorus-Removal Capability**

    - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** The manufacturer says 90-99% of phosphorus is removed, according to af Petersens (2003). Data from the two units tested by Stockholm Water show lower removal rates. One unit had a crack in the wall and was replaced with a newer model which was in operation September 2001 - December 2002; the new unit had an average removal of 90% (Hellström *et al.* 2003). For the first two years of the study, phosphorus in the effluent "was high for long periods of time, because of too low dosage of the precipitant or because of problems with the doser. In 2002, effluent concentrations were noticeably lower for both units..." The data (Fig. 30 in Hellström *et al.* 2003) show effluent total phosphorus concentrations scattered widely between 1 and 20 mg/L the first two years, and almost all samples at or below 4 mg/L during the final 15 months.

- **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** PO_4-P, P_{tot}

- **How does phosphorus concentration affect removal capability?** No information.

- **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** No information.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** From examining graphics of data from Figures 26 and 30 in Hellström *et al.* (2003), it seems that the range of influent phosphorus concentrations did not change systematically from the beginning to end of the study. Yet the effluent concentrations were much lower in the final 15 months of the study. So performance could vary quite a bit, apparently, even without large variations in flow and wastewater composition.

  - **Under what climatic conditions were the tests conducted?** Stockholm: Comparable to Boston in the winter and coastal Maine in the summer.

  - **How does ambient temperature affect the system?** Visual inspection of the data graphics shows no temperature effects.

  - **What range of applications is the alternative designed for?** Single-family house.

- **Maintenance Requirements**

  - **How often is maintenance required?** When the unit is operated at capacity, the sludge should be pumped twice annually, and visual inspection ought to occur once a month, according to af Petersens (2003). The chemical precipitant is refilled when needed, about twice annually. Yet according to (Hellström *et al.* 2003), the standard service contract includes one visit with inspection annually, plus any repairs needed. Of the two units in Stockholm Water's test, one was completely replaced after just a few months (incorrect installation) and the other was completely replaced after 18 months or so (crack in wall). The chemical dosing pump in one unit was replaced twice and its control unit once; the other unit's chemical dosing pump was replaced once.

- **How does lack of maintenance affect system performance?** Presumably, sludge not pumped would carry over into the soil absorption system. If there were problems with any of the pumps or the control of the chemical dosing, nitrogen and phosphorus removal would be impaired.

- **What type of maintenance is required? How difficult is it to perform?** Visual inspection monthly, sludge pumping twice a year, chemical refilling twice a year, detailed inspection once a year.

- **Is there a sorptive material to be replaced?** No.

- **Is there a residual to be disposed of?** Yes

  - **If so, how is it disposed of?** Not discussed in literature. Probably the same way as septage.

  - **How often is this required, and what are the quantities?** Twice a year. Quantities not reported. They can be estimated from Hellström *et al.* (2003), who reported that the total volume of the original units was 2 m^3, and the newer, replacement unit was 4 m^3. If the sedimentation chamber is half the volume, and it is allowed to get 75% full, then the older units would produce 1.5 m^3 (400 gallons) of sludge annually, and the newer unit would produce 3 m^3 (800 gallons) annually.

- **Phosphorus-Recycling Capability**

  - **How available is the phosphorus removed from wastewater for plant uptake?** No information.

  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** None noted. In the Stockholm Water study (Fig. 35, Hellström *et al.* 2003), the cadmium, mercury, and lead levels in the sludge were roughly 8 mg/kg P, 3 mg/kg P, and 225 mg/kg P, respectively. This is about 10% of the levels in the septic tank sludge for the same facility, and the sludge levels for these three metals were less than one third as high as those of the sludge from Bromma wastewater treatment plant, which is considered to have high quality sludge for agriculture.

  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** 69 g/kg dry weight of the sludge. No information on moisture content of the wet sludge.

- **Other Treatment Effects**

    - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** None reported.

    - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** Stockholm Water study: Nitrogen removal 60-90% for one unit, 35-70% for the other. BOD reduction is over 90%. Ammonia-N was at less than 4 mg/L in effluent from one unit and often between 20 and 40 mg/L for the other.

- **Impact on Landscape**

    - **Is the alternative visible or underground?** In the ground.

- **Design**

    - **On what type of sites (soils, etc.) is the technology appropriate to use?** No constraints.

    - **Any odor issues to consider in siting the technology?** The two users interviewed in the Stockholm Water study both reported odor problems from the units, though one said that they ceased toward the end of the study.

    - **What are the dimensions (size) of the technology?** For the newer, 4 m^3 units: 2445 mm high, 2240 mm in diameter, 400 kg (af Petersens 2003).

    - **How easily can the technology be used in a retrofit situation?** It requires a place in the ground between the existing septic tank and the soil absorption system.

    - **Are any changes in user behavior required for this technology to work?** No.

- **Energy Requirements**

    - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** Independent of flow, 880 kWh/year, for aeration of the second and third biological steps and two air-lift pumps for movement of the water from chamber to chamber.

- **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** Sludge production of approximately 800 gallons per year in the newer, 4 m^3 units.

- **Cost**

  - **What is the installation cost?** 57,000 Swedish crowns (SEK) to purchase the unit in Sweden, installation extra. At exchange rate 1 USD = 7.47 SEK (2004.09.17), this converts to = $7,600. Construction and installation costs estimated to be $9,700 more than conventional septic system.

  - **What are the operating and maintenance costs?** In Sweden, about 6,000 SEK ($750) annually. Operation and maintenance costs over 30-year life cycle estimated to be $35,000 more than conventional septic system. The total life-cycle costs are $44,000 (due to rounding).

Sequencing Batch Reactor

Manufacturer: Generic technology

Type of Phosphorus-Removal Technology (check one):

☐ Source reduction

☐ Source separation

☐ Septic tank or substitute for septic tank

☒ Post-septic tank, pre-SAS

☐ Soil absorption system

☐ Other

Describe the Technology and How It Removes Phosphorus:

General Description:

There are many manufacturers. The one investigated in detail is a package treatment plant designed to be kept in the cellar. It uses a sequencing batch reactor and chemical precipitation of phosphorus. They are manufactured for 1-7 households or 5-35 P.E. (person equivalents). The company also makes package treatment plants for larger systems. The version described here is designed for 5 P.E.

Technical Description:

The system investigated consists of a collection tank, a sequencing batch reactor (SBR), and a sludge-drying unit. The collection tank, which can be the septic tank, evens out the flows in the SBR. Wastewater is pumped from there to the SBR, which has a capacity of 250 L (66 gallons) per batch. The SBR cycle is five hours long and consists of three hours aeration with dosing of an aluminum-based precipitant after two hours, sedimentation for 90 minutes, and emptying for 30 minutes. The effluent continues to the soil absorption system, and the excess sludge is sent to one of two sludge filter bags (used alternately), where it is dried by air blown through it. When the activated sludge chamber is between cycles, it is aerated 30 minutes every hour. Some sludge is recirculated as return sludge, to the collection tank.

Answer the following questions, give the reference for all information, and describe briefly how the tests were conducted. Use ranges of numbers wherever appropriate, and, if known, note what the frequency distribution is within the range and what determines where within the range a system falls.

- **What is the appropriate application of this alternative? Check as many as apply:**

☒ Single-family residence

☒ Cluster system

☐ Large system, over 3,500 gallons per day

☐ Commercial system (restaurant, strip mall, etc.)

- **Proven Track Record**

  - **How long has the phosphorus-removal alternative been used?** The company reports being founded in 1982.

  - **How many different units have been used?** Many. The manufacturer of the unit investigated reports more than 3,500 package treatment plants in Norway. It is reported by af Petersens (2003) that about 3,000 have been sold in Norway and 350 in Sweden.

  - **Under what conditions have they been used?** Norwegian, Swedish.

  - **Describe the number and sources of data to support claims of phosphorus removal. E.g., manufacturer testing, third party evaluation, etc.** Independent data from a third party evaluation by Stockholm Water, the water/wastewater utility for Stockholm, Sweden (Hellström *et al.* 2003). Two units were used in single-family houses in this three-year study just south of Stockholm that began in early 2000. One unit was installed at the beginning of the study in a household with two adults. After that household was reduced to one adult, an additional unit was installed in a household with four persons, and it was in operation for approximately the last nine months of the study. Also independently evaluated by the municipality of Västerås, according to af Petersens (2003). It’s not clear that af Petersens used the Västerås data.

- **Phosphorus-Removal Capability**

  - **What percentage of phosphorus is removed? If known, answer in terms of a range, and what affects the range (including age of system or medium used).** Phosphorus removal was estimated from test results in the Stockholm Water study, because of difficulties in testing. The incoming water test was taken in the collection tank. However, they report that some sedimented solids were on the bottom of the tank and some of the return sludge flowed back into the collection tank. The small tank for sampling of the outgoing water also accumulated some sludge. With those caveats, the following estimates were reported: The first unit removed 0-70% of the phosphorus during the first 18 months of the study, when the single unit had many operational problems. During the last 9 months of the study, the first and added, second unit showed removal uniformly over 70% and predominantly over 80%.

  - **How is phosphorus measured and reported? E.g., phosphate P, P_{tot}.** Phosphate, P_{tot}.

  - **How does phosphorus concentration affect removal capability?** No information.

  - **Do other water chemistry factors (e.g., pH, BOD, TSS, NO_3^-, NH_3^+) affect removal capability?** No information.

- **Robustness of the System**

  - **How is the system's performance affected by variations in flows and in wastewater composition?** No information from the Stockholm Water data. According to the US EPA (2002), SBR technology produces more reliable effluent quality for individual homes than continuous flow-activated sludge or fixed-film systems, because spikes in flows and constituents are evened out. SBR reactors are not suited for seasonal use.

  - **Under what climatic conditions were the tests conducted?** Near Stockholm: winters comparable to Boston, summers comparable to coastal Maine. Reactors were kept in insulated buildings.

  - **How does ambient temperature affect the system?** It's not clear what the ambient temperature was in the reactors in the insulated buildings.

  - **What range of applications is the alternative designed for?** The company builds systems for everything from one house to municipal size.

- **Maintenance Requirements**

  - **How often is maintenance required?** According to af Petersens (2003), the sludge drying unit with its sludge sacks means that sludge can be removed by hand. The sludge can be composted and used in the garden (depending on local rules). A standard service contract with the company encompasses three visits per year.

  - **How does lack of maintenance affect system performance?** In the Stockholm Water study, a number of technical problems developed. Results ranged from effluent with high levels of suspended solids and phosphates to spills of wastewater onto the floor of the room the unit was contained in. These incidents were mechanical failures, presumably not due to lack of maintenance.

- **What type of maintenance is required? How difficult is it to perform?** The sludge sacks are emptied, the precipitant is refilled, the mechanical equipment is checked, and effluent quality is sampled. The sludge sacks can easily be changed by the user, who can also refill the precipitant. Other maintenance requires a trained service provider. The Stockholm Water employees recommend that the user have routines for inspection of the controls. No sludge pumping of the collection tank is required, according to af Petersens (2003) and Hellström *et al.* (Hellström *et al.* 2003).

- **Is there a sorptive material to be replaced?** No.

- **Is there a residual to be disposed of?** Yes

  - **If so, how is it disposed of?** Can be composted and used in garden, depending on local rules.

  - **How often is this required, and what are the quantities?** The information is not explicit. Apparently emptying the sludge sacks is not required more than three times a year, and the quantities are characterized as small (af Petersens 2003; Hellström *et al.* 2003) Sludge dry matter content is 12-14% (Hellström *et al.* 2003).

- **Phosphorus-Recycling Capability**

  - **How available is the phosphorus removed from wastewater for plant uptake?** No information.

  - **Are there any environmental or health barriers to recycling the phosphorus to agriculture, e.g., contamination with heavy metals?** No information.

  - **How concentrated is the phosphorus (this affects economic viability of recycling)?** 36 g/kg dry weight sludge, and the sludge is 12-14% dry matter.

- **Other Treatment Effects**

  - **As phosphorus is removed, is there a significant change in the chemical makeup of the remaining solution (e.g., pH, D.O., electrolytes, other secondary compounds)?** None reported.

  - **What other wastewater treatment benefits are achieved by the alternative, in addition to phosphorus removal? E.g., nitrification, denitrification, reduction in BOD, reduction in TSS? Quantify.** BOD removal was at or above 75% at all times in the Stockholm Water study, and well over 90% when the units were functioning well. Nitrogen removal varied widely, mostly between 30% and 80%.

- **Impact on Landscape**
  - **Is the alternative visible or underground?** The version evaluated is designed to be in an insulated building—either the basement or a separate outbuilding. For single-family homes only, a version is available which can be installed underground, with all moving parts still above ground (Goodtech Biovac AS 2004).

- **Design**
  - **On what type of sites (soils, etc.) is the technology appropriate to use?** No particular restrictions.
  - **Any odor issues to consider in siting the technology?** None reported.
  - **What are the dimensions (size) of the technology?** $210 \times 300 \times 210$ cm
  - **How easily can the technology be used in a retrofit situation?** Both the underground and in-house version could work, depending on whether there is room.
  - **Are any changes in user behavior required for this technology to work?** Some regular checking on the system is necessary to ensure it is working properly. The compressor makes a low noise which can be audible throughout the house.

- **Energy Requirements**
  - **How much electricity is needed to operate the system? Specify whether electricity use is flow dependent or not. If it is not flow dependent, use units of kWh/year for a system of a specified size. If it is flow dependent, use units of kWh/year per 100 gallons/day treatment. Specify where the electricity is used.** 450 kWh/year to run the aerator, pumps.
  - **How much non-electric energy is used to operate the system, e.g., diesel to transport waste products? Specify whether energy use is flow dependent or not. Specify how and where the energy is used, so that the project leader can use a common set of assumptions for each technology to convert to energy use. E.g., "The 1000 gallon septic tank is emptied every three years and the septage is hauled by truck to a wastewater treatment plant."** A small amount of sludge which can be composted and used locally, or hauled away and composted.

- **Cost**

  - **What is the installation cost?** Purchase and installation cost 79,000 SEK in Sweden. At exchange rate 1 USD = 7.47 SEK (2004.09.17), this converts to $10,600. This presupposes there is unused space in the basement or elsewhere for the unit. Construction and installation costs estimated to be $11,000 more than conventional septic system.

  - **What are the operating and maintenance costs?** Around 3,000 SEK ($350) annually, in Sweden. Operation and maintenance costs over 30-year life cycle estimated to be $26,000 more than conventional septic system. Thirty-year life-cycle cost is estimated to be $37,000 more than a conventional septic system.

B DETAILED DATA TABLE USED IN BIOTA SCREENING PROCESS

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Aquatic Macrophytes	Duckweed	Lemnaceae	N/R	N/R	600	N/R	(Culley Jr. and Epps 1973)
		Lemnaceae	4.1	74-92	N/R	N/R	(Zimmo *et al.* 2002)
		Lemnaceae	1.3-14.3	50-99	N/R	0.3-1.4	(Korner and Vermaat 1998)
		Lemna minor L	15	31-96.7	N/R	N/R	(Obek and Hasar 2002)
		Lemnaceae	N/R	30-50	N/R	1.5	(Leng 1999)
		Lemnaceae	N/R	12-92	N/R	N/R	(Oron *et al.* 1984)
		Lemnaceae	13	11-43	N/R	N/R	(Nhapi *et al.* 2003)
		Lemnaceae	N/R	16	220	0.8-1.8	(Reed 1995)
		Lemnaceae	N/R	60-92.2	N/R	N/R	(Hammouda *et al.* 1995)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Aquatic Macrophytes	Water Hyacinth	*Eichhornia crassipes*	N/R	N/R	1350	0.8	(DeBusk and Reddy 1989)
		Eichhornia crassipes	N/R	N/R	350-1125	N/R	(Reddy and DeBusk 1987)
		Eichhornia crassipes	N/R	N/R	896	0.4	(Tourbier 1976)
		Eichhornia crassipes	4.70-8.24	8-29	N/R	N/R	(NASA/NSTL 1980)
		Eichhornia crassipes	N/R	74-87	N/R	N/R	(Tourbier 1976)
Aquatic Macrophytes	Water Hyacinth	*Eichhornia crassipes*	4.74-6.72	4-19	N/R	N/R	(NASA/NSTL 1980)
Aquatic Macrophytes	Water Hyacinth	*Eichhornia crassipes*	2.6-5.8	35-80	N/R	N/R	(NASA/NSTL 1980)
		Eichhornia crassipes	4.74-6.18	3-23	N/R	N/R	(NASA/NSTL 1980)
		Eichhornia crassipes	3.44	1-43	N/R	N/R	(NASA/NSTL 1980)
		Eichhornia crassipes	4.74-6.72	10-23	N/R	N/R	(NASA/NSTL 1980)
		Eichhornia crassipes	10	90	0.5-5	N/R	(Reddy and DeBusk 1987)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
		Eichhornia crassipes	1.95	85	N/R	N/R	(Cloris and Aruajo 1987)
		Eichhornia crassipes	1.46	81	169	N/R	(DeBusk 2001)
		Eichhornia crassipes	0.3	67	180	N/R	(DeBusk 2001)
		Eichhornia crassipes	0.74	53	296	N/R	(DeBusk 2001)
		Eichhornia crassipes	1.06	48	519	N/R	(DeBusk 2001)
		Eichhornia crassipes	6.12-6.66	38	N/R	N/R	(NASA/NSTL 1980)
		Eichhornia crassipes	4.33	21	N/R	N/R	(NASA/NSTL 1980)
Aquatic Macrophytes	Water Hyacinth	*Eichhornia crassipes*	4.33	14	515	N/R	(DeBusk 2001)
Aquatic Macrophytes	Water Hyacinth	*Eichhornia crassipes*	4.68	10	113	N/R	(DeBusk 2001)
Hydroponic	Ostinata lettuce and sweet basil	N/R	0.016	99	365	0.4-0.45	(Adler *et al.* 1996)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Macroalgae and Periphyton	Periphyton	N/R	3-5	>95	N/R	2.1	(Craggs 2001)
		N/R	N/R	>90	N/R	N/R	(Hemens and Mason 1968)
		N/R	12	98	N/R	N/R	(Jackson and Jackson 1972)
		N/R	3-5	76	N/R	N/R	(Bush *et al.* 1963)
		N/R	3.1	48	1600	1.83	(Craggs 2001)
Reed Beds and Wetlands	Alluvial cypress swamp	N/R	N/R	N/R	9	N/R	(Mitsch and Dorge 1979)
Reed Beds and Wetlands	Bulrush	*Schoeno-plectus tabernae-montani*	15	9-14	486	N/R	(Tanner *et al.* 1999)
		Scirpus lacustris	N/R	79-90	N/R	N/R	(Soto *et al.* 1999)
		Scirpus validus	1.28	50	N/R	N/R	(Coleman *et al.* 2001)
		Scirpus	N/R	35	N/R	N/R	(Soto *et al.* 1999)
Reed Beds and Wetlands	Cattail	*Typha glauca*	N/R	N/R	65	0.25	(Bernard 1999)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Reed Beds and Wetlands	Cattail	*Typha latifolia*	1.28	80	N/R	N/R	(Coleman *et al.* 2001)
Reed Beds and Wetlands	Cattail, bulrush	*Typha latifolia, Scirpus americanas*	74.81	30-45	33-39	N/R	(Reddy *et al.* 2001)
Reed Beds and Wetlands	Cattail, Phragmites, Iris	*Typha latifolia, Phragmites australis, Iris pseudacorus*	N/R	63-96	N/R	N/R	(Mander *et al.* 2000)
Reed Beds and Wetlands	Cattail, smartweed	*Typha latifolia, Polygonum punctatum*	52	96	N/R	N/R	(Schaafsma *et al.* 2000)
Reed Beds and Wetlands	Cypress dome	N/R	N/R	N/R	0	N/R	(Dierberg 1980)
Reed Beds and Wetlands	Cypress dome receiving wastewater	N/R	N/R	N/R	1	N/R	(Dierberg 1980)
Reed Beds and Wetlands	Cypress swamp	N/R	N/R	N/R	3	N/R	(Schlesinger 1978)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Reed Beds and Wetlands	Cypress swamp receiving wastewater	N/R	N/R	N/R	23	N/R	(DeBusk 1984)
Reed Beds and Wetlands	Cypress swamp receiving wastewater	N/R	N/R	N/R	15	N/R	(Nessel and Bayley 1984)
Reed Beds and Wetlands	Flattened hemarthia	*Hemarthria compressa*	0.038-1.6	77	225	N/R	(Liu *et al.* 2000)
Reed Beds and Wetlands	Floodplain Forest	N/R	N/R	N/R	1	N/R	(Brown 1981)
Reed Beds and Wetlands	Limpograss	*Hemarthria altissma* Poir	0.038-1.6	77	102	N/R	(Liu *et al.* 2000)
Reed Beds and Wetlands	N/R	N/R	9	73-85	N/R	N/R	(Laquali *et al.* 1998)
Reed Beds and Wetlands	N/R	*Datura innoxia*	9	29-47	N/R	N/R	(Vaillant *et al.* 2003)
Reed Beds and Wetlands	N/R	N/R	8.5	91	N/R	N/R	(Schönborn *et al.* 1996)
Reed Beds and Wetlands	Napiergrass	*Pennisetum purpurem*	0.038-1.6	83	424	N/R	(Liu *et al.* 2000)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Reed Beds and Wetlands	Napiergrass	*Pennisetum purpurem*	0.038-1.6	83	333	N/R	(Liu *et al.* 2000)
Reed Beds and Wetlands	Phragmites	*Phragmites australis*	N/R	N/R	19	0.11	(Kvet 1973)
Reed Beds and Wetlands	Phragmites	*Phragmites australis*	N/R	N/R	7	0.05	(Peverly *et al.* 1993)
Reed Beds and Wetlands	Phragmites	*Phragmites australis*	10.6	6-22	89	0.2	(Meuleman *et al.* 2002)
Reed Beds and Wetlands	Phragmites	*Phragmites australis*	10.6	6-22	19-70	0.2	(Meuleman *et al.* 2002)
Reed Beds and Wetlands	Phragmites	*Phragmites australis*	1.5	99	N/R	N/R	(Bernard 1999)
Reed Beds and Wetlands	Phragmites	*Phragmites australis*	10.6	6	19	0.2	(Meuleman *et al.* 2002)
Reed Beds and Wetlands	Reed Canary grass	*Phalaris arundindacea*	0.038-1.6	60	87	N/R	(Liu *et al.* 2000)
Reed Beds and Wetlands	Reed canary grass	*Phalaris arundindacea*	0.038-1.6	60	262	N/R	(Liu *et al.* 2000)
Reed Beds and Wetlands	Rice Yuanyou 1	*Oryza sativa* L.	0.038-1.6	76	749	N/R	(Liu *et al.* 2000)
Reed Beds and Wetlands	Rice Suakoko 8	*Oryza sativa* L.	0.038-1.6	79	778	N/R	(Liu *et al.* 2000)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Reed Beds and Wetlands	Sedge	*Carex lacustris*	N/R	N/R	16	0.14	(Bernard and Solsky 1977)
Reed Beds and Wetlands	(similar to Juncus)	*Zisaniopsis bonariensis*	47	72	N/R		(Philippi *et al.* 1999)
Reed Beds and Wetlands	Teosinte	*Olzea mexicana*	0.038-1.6	83	394	N/R	(Liu *et al.* 2000)
Reed Beds and Wetlands	Water spinach	*Ipomoea aquatica*	0.038-1.6	81	473	N/R	(Liu *et al.* 2000)
Submerged Aquatic	Coontail + southern Naiad	*Cerato-phyllum Demersum + Najas Guadalu-pensis*	N/R	48	10	N/R	(Nungesser and Chimney 2001)
Terrestrial Macrophytes (non-woody)	Alfalfa	N/R	N/R	N/R		N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Barley	N/R	N/R	N/R	15	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Bermuda grass sod	*Cynodon dactylon*	125, 200 kgP/ha	46	57-92	N/R	(Vietor *et al.* 2002)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Terrestrial Macrophytes (non-woody)	Bromegrass	N/R	N/R	N/R	39.2-56	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Buffalo grass sod	*Buchloe dactyloides*	103, 212 kgP/ha	57	59-121	N/R	(Vietor *et al.* 2002)
Terrestrial Macrophytes (non-woody)	Corn	N/R	N/R	N/R	20	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Costal Bermuda grass	N/R	N/R	N/R	33.6-44.8	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Cotton	N/R	N/R	N/R	15	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Fescue "Fuego"	N/R	N/R	N/R	8	0.32	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Fescue "AU triumphoSei"	N/R	N/R	N/R	8	0.31	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Fescue "Barcarella"	N/R	N/R	N/R	9	0.35	(Downing 2002)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Terrestrial Macrophytes (non-woody)	Fescue "Barolex"	N/R	N/R	N/R	9	0.37	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Fescue "Seine"	N/R	N/R	N/R	8	0.33	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Grain Sorghum	N/R	N/R	N/R	15	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Kentucky Bluegrass	N/R	N/R	N/R	45	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Orchard Grass	N/R	N/R	N/R	20.1-50.4	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Orchard Grass "Baridana"	N/R	N/R	N/R	8.43-12.1	0.34	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Orchard Grass "Cambria"	N/R	N/R	N/R	8.40-9.34	0.32	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Orchard Grass "Orion"	N/R	N/R	N/R	7.18-12.7	0.34	(Downing 2002)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Terrestrial Macrophytes (non-woody)	Orchard Grass "Pizza"	N/R	N/R	N/R	8.40-11.4	0.37	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Potatoes	N/R	N/R	N/R	20	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Quackgrass	N/R	N/R	N/R	28.0-44.8	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Redtop, rough bluegrass, reed canary grass	*Agrostis alba, Pao trivialis, Phalaris arundinacea*	0.48	>90	N/R	N/R	(Adler *et al.* 1996)
Terrestrial Macrophytes (non-woody)	Reed Canary grass	N/R	N/R	N/R	39.2-44.8	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Ryegrass	N/R	N/R	N/R	56.0-84.0	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Ryegrass "Barfort"	N/R	N/R	N/R	8.10-10.2	0.34	(Downing 2002)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Terrestrial Macrophytes (non-woody)	Ryegrass "Bellramo"	N/R	N/R	N/R	7.90-10.3	0.34	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Ryegrass "Bg-34"	N/R	N/R	N/R	9.34-11.9	0.35	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Ryegrass "Bronsyn"	N/R	N/R	N/R	9.29-9.63	0.34	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Ryegrass "Elgon"	N/R	N/R	N/R	8.92-9.78	0.35	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Ryegrass "Glenn"	N/R	N/R	N/R	8.43-10.5	0.36	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Ryegrass "Herbie"	N/R	N/R	N/R	9.01-10.2	0.35	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Ryegrass "Tonga"	N/R	N/R	N/R	7.01-11.3	0.34	(Downing 2002)
Terrestrial Macrophytes (non-woody)	Soybeans	N/R	N/R	N/R	11.2-20.2	N/R	(Crites *et al.* 2000)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Terrestrial Macrophytes (non-woody)	Sweet Clover	N/R	N/R	N/R	20	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Tall Fescue	N/R	N/R	N/R	30	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (non-woody)	Wheat	N/R	N/R	N/R	14	N/R	(Crites *et al.* 2000)
Terrestrial Macrophytes (Trees)	Eucalyptus	*Eucalyptus globules*	N/R	N/R	11.6-18.3	N/R	(Guo *et al.* 2002)
Terrestrial Macrophytes (Trees)	European Larch	*Larix deciduas*	N/R	N/R	1	N/R	(Son and Gower 1992)
Terrestrial Macrophytes (Trees)	N/R	*Salix viminalis* "Bjorn"	10	N/R	17	N/R	(Gregersen and Brix 2001)
Terrestrial Macrophytes (Trees)	N/R	*Salix viminalis* "Jorr"	10	N/R	19	N/R	(Gregersen and Brix 2001)
Terrestrial Macrophytes (Trees)	N/R	*Salix viminalis* "Tora"	10	N/R	15	N/R	(Gregersen and Brix 2001)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (Mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Terrestrial Macrophytes (Trees)	N/R	*Fraxinus excelsior* L.	5.2	4-7	N/R	NL	(Nemcova *et al.* 1999)
Terrestrial Macrophytes (Trees)	N/R	*Prunus padus* L.	5.2	3-6	N/R	N/R	(Nemcova *et al.* 1999)
Terrestrial Macrophytes (Trees)	N/R	*Salix cinerea* L.	5.2	24-28	N/R	N/R	(Nemcova *et al.* 1999)
Terrestrial Macrophytes (Trees)	N/R	*Populus tremula* L.	5.2	14-17	N/R	N/R	(Nemcova *et al.* 1999)
Terrestrial Macrophytes (Trees)	N/R	*Alnus glutinosa* L.	5.2	16	N/R	N/R	(Nemcova *et al.* 1999)
Terrestrial Macrophytes (Trees)	N/R	*Alnus cordata* L.	5.2	9	N/R	N/R	(Nemcova *et al.* 1999)
Terrestrial Macrophytes (Trees)	Norway spruce	*Picea abies*	NR	N/R	3	N/R	(Son and Gower 1992)
Terrestrial Macrophytes (Trees)	Poplar	*Populus deltoidsnigra*	N/R	N/R	7.5-11.2	0.11	(Flaherty 2002)

Table B-1
Summary of Plant Species and Biotic Communities Reviewed for Phosphorus-Removal Potential (Cont.)

Category	Common Name	Latin Name	Influent P (mg/L)	% P Removal	Kg/Ha/Yr P Sequestered	P As % Of Organism's Dry Weight	Reference
Terrestrial Macrophytes (Trees)	Red oak	*Quercus ruba*	N/R	N/R	1	N/R	(Son and Gower 1992)
Terrestrial Macrophytes (Trees)	Red pine	*Pinus resinosa*	N/R	N/R	2	N/R	(Son and Gower 1992)
Terrestrial Macrophytes (Trees)	White pine	*Pinus strobes*	N/R	N/R	2	N/R	(Son and Gower 1992)

N/R = Not Reported

Printed on recycled paper in the United States of America.

WU-HT-03-22

NDWRCDP
Washington University, Campus Box 1150, One Brookings Drive, Cupples 2, Rm. 11, St. Louis, Missouri 63130-4899 • USA

*This report is available online at www.ndwrcdp.org. This report is also available through the
National Small Flows Clearinghouse • West Virginia University/NRCCE, P.O. Box 6064, Morgantown, WV 26506-6064 • USA
Tel: (800) 624-8301 • WWCDMG45*