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EVALUATION OF WASTEWATER TREATMENT OPTIONS USED IN RAPID INFILTRATION BASIN SYSTEMS (RIBS)

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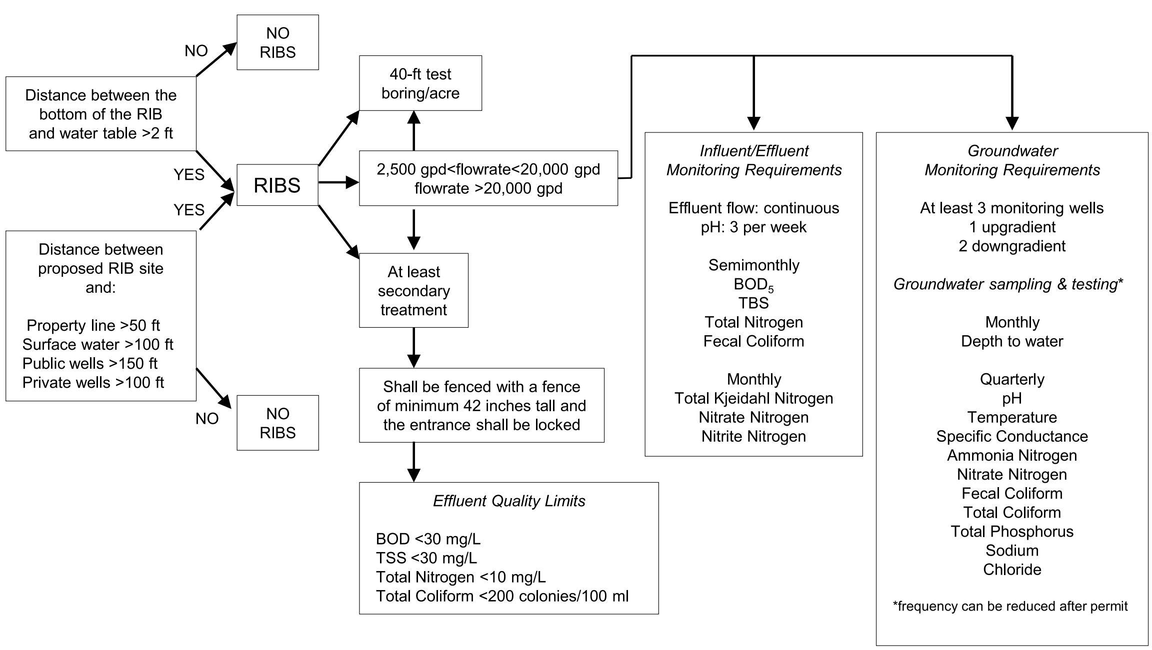

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ACRONYMS USED IN THIS REPORT

AS	Activated Sludge
BC	Beaver Creek
BCF	Breeder's Crown Farm
BOD	Biochemical Oxygen Demand
CE	Colonial Estates
CH	Cape Henlopen State Park
COD	Chemical oxygen demand
col/100 ml	Colonies per 100 milliliters
DE	Delaware
DGS	Delaware Geological Survey
DNREC	Delaware Department of Natural Resources and Environmental Control
EA	Extended aeration
FG	Forest Grove
IT	Imhoff tank
LBWD	Land based wastewater disposal
LSA	Landis Sewerage Authority
MA	Massachusetts
MD	Maryland
μg/L	Micrograms per liter
mg/L	Milligrams per liter
N	Nitrogen
NC	North Carolina
NH_4^-	Ammonia
NJ	New Jersey
NO_3^-	Nitrate
O&M	Operation and maintenance
OD	Oxidation ditch
OP	Ortho-Phosphorus
P	Phosphorus
RBC	Rotating biological contactor
RIBS	Rapid infiltration basin systems
SBR	Sequencing batch reactor
SMWW	Standard Methods for Examination of Water and Wastewater
SWA	Southwood Acres
SC	Stonewater Creek
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TMDL	Total Maximum Daily Load
TP	Total phosphorus
TSS	Total suspended solids
USEPA	U.S. Environmental Protection Agency
WBP	West Bay Park
WTP	Winslow Township
WWTP	Wastewater treatment plant

EVALUATION OF WASTEWATER TREATMENT OPTIONS USED IN RAPID INFILTRATION BASIN SYSTEMS (RIBS)

ABSTRACT

This technical report evaluates several aspects of potential environmental risks, use, and regulation of rapid infiltration basin systems (RIBS) in Delaware. The report reviews and compares regulations regarding RIBS from Delaware, Florida, North Carolina, New Jersey, Maryland, and Massachusetts. Influent and effluent samples from ten advanced wastewater treatment systems that operate in conjunction with RIBS were collected and analyzed. Effluent data obtained from the Non-Hazardous Waste Sites database provided by the Delaware Department of Natural Resources and Environmental Control and other states were assessed. Performance evaluations of the treatment processes that discharge to RIBS were ascertained from the exceedance of concentrations of regulated pollutants in effluent samples.

Although RIBS technology has the potential to be a beneficial alternative to surface discharge and a means for groundwater recharge, this technology is appropriate only if the adverse environmental impacts are minimized. Overall operation and maintenance practices play important roles in the performance of treatment plants. The most common and serious problems associated with treatment plants located in Delaware and neighboring states are high nutrient and pathogen concentrations in the effluent. In Delaware, the discharge of poorly treated effluent to RIBS creates a risk of nutrient and pathogen contamination in the receiving water body, the shallow Columbia aquifer. Years of application of treated effluent with high nutrient, pathogen, and organic content to RIBS will result in significant risks for the environment and public health.

INTRODUCTION

For hundreds of years, people have disposed of their wastewater directly into surface waters. The land application of wastewater is also a long standing practice for many communities (William and Belford, 1979; Bastian, 2005; Williams, 2006; Reed et al., 1984). However, as environmental awareness has increased, local governments are often required to both treat their wastewater, and find efficient and beneficial disposal options for their wastewater. By law, wastewater collected from residences, industries, and institutions now either must be returned to receiving waters, applied to the land, or reused. The level of treatment prior to discharge determines the impact of effluent on the receiving environment.

Land-based wastewater disposal (LBWD) is the controlled application of treated effluent onto the soil, where it receives additional treatment. LBWD methods have been used in the United States since the late 19th century, especially in the relatively arid, rapidly developing, west and southwest, where low water supplies make water reuse and groundwater recharge essential. The use of LBWD methods is now spreading into other locations.

One type of LBWD is RIBS, a land treatment system that resembles intermittent sand filtration. With RIBS, pretreated wastewater is applied to an infiltration basin, from which it percolates through the soil and into the groundwater. The method is also known as soil-aquifer treatment because physical, chemical, and biological mechanisms further treat the wastewater as it moves downward (Crites and Tchobanoglous, 1998; Asano et al., 2006). When properly operated, RIBS may recharge the groundwater, provide further treatment to the treated effluent, and reduce the degradation of stream-water quality. Some selected RIBS are shown in Table 1.

Table 1. Selected RIBS in the United States.

Location	Hydraulic Loading Rate (ft/yr)
Brookings, South Carolina	40
Calumet, Michigan	115
Darlington, South Carolina	92
Fresno, California	44
Hollister, California	50
Lake George, New York	190
Orange County, Florida	390
Tucson, Arizona	331
West Yellowstone, Montana	550

Crites, Middlebrooks, and Reed, 2006; Asano et al., 2006

Wastewater and the Environment

Municipal wastewater contains a variety of solid materials that differ in type, size, and density. Typical domestic wastewater contains 350-1200 mg/L total solids, 100-350 mg/L total suspended solids (TSS), 280-860 mg/L total dissolved solids, and 5-20 mg/L settleable solids (Crites and Tchobanoglous, 1998). During treatment, coarse particulate are removed by settling. Usually 60 percent of the suspended solids are settleable; after settling they are removed (Tchobanoglous and Stensel, 2003). Some of the remaining suspended solids are removed by filtration or entrapment if the effluent is land applied. Alternating flooding-drying cycles during land application allow these solids to desiccate or degrade. However, to prevent clogging and hydraulic failure in a RIBS application, dried solids need to be removed from the surface of the application area or the area must be routinely scraped to prevent clogging and hydraulic failure. Inadequate procedures for removing solids can increase the risk that the groundwater will be contaminated by certain types of bacteria (Tchobanoglous and Stensel, 2003).

In nature, pollutants may be degraded biologically or chemically. When biodegradable carbonaceous organic materials are released into a body of water, microorganisms break them into smaller organic and inorganic molecules to meet their carbon and energy requirements. When this happens under aerobic conditions, the amount of oxygen the microorganisms consume is called biological oxygen demand (BOD). When a lot of oxygen is needed for microorganisms to break down the pollutants, all of the oxygen in the receiving environment may be depleted. A lack of oxygen kills off fish and other animals in the region resulting in an environmental problem that is called eutrophication. Therefore, BOD is the most widely used parameter to determine the level of organic pollution in wastewaters and surface waters.

Similarly, chemical oxygen demand (COD) is used to determine the amount of oxygen required to oxidize pollutants chemically. A strong chemical oxidizing agent, commonly potassium dichromate, is used to oxidize the organics in a COD test. BOD has traditionally been a more commonly used measure of the strength of organic pollution because treated effluents were disposed into an aquatic environment. However, for this project, we analyzed effluent samples for both BOD and COD since, in the groundwater environment, some of the complex organic substances are hard to oxidize biologically but can be oxidized chemically.

Oxygen is also required for biodegradation of noncarbonaceous matter, such as ammonia (NH_4^-). In biological wastewater treatment, the oxidation of ammonium (NH_4^-) to nitrate (NO_3^-) consumes at least 40 percent of the total oxygen; competition for oxygen between heterotrophic bacteria and nitrifying bacteria (*Nitrosomonas, Nitrobacter*) is normally the limiting factor for the conversion of organic matter and NH_4^-. In most cases, heterotrophic bacteria outcompete the slow-growing nitrifying bacteria, which die off due to lack of oxygen. In most cases, any biological treatment system without a separate nutrient removal unit is insufficient to meet the oxygen requirements of the system (Henze et al., 1997). However, better nutrient reduction also leads to the removal of pharmaceuticals and personal care products (Cristen, 2006). For complete nitrogen (N) removal, denitrifying bacteria *(Flavobacteria, Bacillus, Micrococcus)* must reduce NO_3^- to N gas under anoxic conditions. When oxygen is completely depleted by heterotrophic and nitrifying bacteria, facultative bacteria may use NO_3^- as an oxygen source and produce N gas (Tchobanoglous and Stensel, 2003; Russell, 2006).

Although both N and phosphorus (P) are essential nutrients for the growth of plants and other organisms, they can be harmful when present in surface waters. Excess N and P is known to trigger algal blooms and accelerate plant growth, ultimately bringing about the death of fish and other animals. Either N or P can be the limiting nutrient in a water body. Typical untreated domestic wastewater contains 4-15 mg/L total phosphorus (TP) (Crites and Tchobanoglous, 1998). P has a dramatic impact on surface waters even at very low concentrations, especially when it is the limiting nutrient in controlling eutrophication. For this reason, it is essential to control P concentrations in treated effluent prior to its discharge. Delaware limits P discharge to bodies of surface water but currently does not have any statewide P restrictions for groundwater.

Wastewater treatment is complicated by the fact that P and N removal do not occur simultaneously. To remove P, wastewater is sequenced into reactors where a group of bacteria use volatile fatty acids as carbon sources and then release P into the system. If the conditions are changed from anaerobic to aerobic, the bacteria take up more P than they release. The P-rich microorganisms become part of the wastewater sludge that is then removed (Crites and Tchobanoglous, 1998; Tchobanoglous and Stensel, 2003).

A major concern regarding treated wastewater is human disease caused by pathogenic organisms. Pathogens that are abundant and easy to test for are used to indicate the presence of human fecal contamination. An ideal indicator organism must be present whenever the target pathogenic organism is present (Tchobanoglous and Stensel, 2003). An example is coliform bacteria, which are found in the human intestinal tract and indicate contamination by human feces. Another example is the pathogen, enterococci, which are found in the intestines of humans and animals, and are responsible for serious infections (Fraser, 2008). Although the enterococci generally occur in lower numbers than fecal coliform, they exhibit better survival in sediment and marine and estuarine waters, and so can be successfully used in the risk assessment of these environments (Tchobanoglous and Stensel, 2003; Jin et al., 2004).

Wastewater and RIBS

Major wastewater constituents can be effectively removed by the rapid infiltration process. Organic pollutants, solids and suspended solids are removed initially by filtration and later by microbial biodegradation. Adsorption of the remaining organic compounds takes place in the soil; therefore to prevent clogging the basin with excessive organic material and solids the loading rate is a very important parameter (Matsumoto and California Water Resources Center, 2004).

Some of the benefits of RIBS include:

- The elimination of the direct discharge of wastewater effluent to surface waters.
- The potential treatment of wastewater effluent through filtration, adsorption and biological degradation.
- The replenishment of groundwater through the discharge of reclaimed water to the RIBS.
- The ability of the process to work in all seasons.
- Economic feasibility, since the process does not require much land.

Environmental Impact of RIBS

With the increase in environmental consciousness, land application sites may be monitored by government agencies, research institutes, and the public to prevent groundwater contamination. In addition, the long-term impacts of RIBS on receiving environments in different regions of the United States have been studied by many researchers (Sumner and Bradner, 1996; Aulenbach and Clesceri, 1980; Quanrud et al., 2003).

Nutrients (N, P), solids, pathogens, and organic compounds are the most common contaminants from RIBS that might reach surface or groundwater sources. N and P can be present in many forms in soil and wastewater depending on the redox potential of the environment. Most of the N species found in water can have adverse effects on living organisms (Stumm and Morgan, 1996). N in water is commonly found as NO_3^-, the most oxidized form of N. High NO_3^- concentrations in drinking water are strongly associated with "blue baby" syndrome, a potentially fatal condition that particularly affects infants (Knobeloch et al., 2000; Masters, 1998). The Safe Drinking Water Act limits NO_3^--N concentration to 10 mg/L for public water supplies (USEPA, June 2003). However while this federal regulation ensures the safety of public water sources, it does not apply to private wells. Thus, site specific, systematic, and detailed research on the potential effects of RIBS on NO_3^- concentrations in the receiving environment is crucial.

RIBS can provide effective natural N reduction in treated wastewater through a series of chemical and biological reactions. N removal depends on environmental conditions such as oxygen availability and temperature. Higher N removal rates are achieved when NH_4^- in influent wastewater is fully oxidized to NO_3^-. Particle size, mineral content, adsorption capacity and biological activity of the soil, treatment processes used to treat the wastewater, and operation strategies all play important roles in N removal (Matsumoto and California Water Resources Center, 2004; Sumner and Bradner, 1996). Because these parameters differ between sites, so do the removal efficiencies. For instance, while the total nitrogen (TN) removal rate for RIBS in Colton, California, is reported to be 78 percent, it is around 50 percent for the Reedy Creek RIBS in Orange County, Florida. The importance of operation strategies in N removal was reported by Bouwer and Rice (1984), who measured almost no N removal during short and frequent flooding periods (2 days flooding, 5-10 days drying), but measured up to 30 percent N removal with longer flooding periods (10 days flooding, 2 weeks drying). Short and frequent flooding makes soil profiles mostly aerobic, which limits NO_3^- to N conversion. No N is removed if the flooding periods are extremely long since the lack of oxygen prevents NO_3^- formation. Because of these limitations, flooding schedules that optimize N removal should be developed for each individual RIB system.

One well-studied land application site in Cape Cod, Massachusetts, has been active for more than 60 years. At the site the disposal of secondarily treated wastewater into RIBS created a contaminated groundwater plume 6000 m long, 30 m thick, and more than 1000 m wide (Repert et al., 2006). Dissolved N (mainly NO_3^- and NH_4^-), P, dissolved organic and inorganic carbon, chloride, boron, organic N and NO_3^- are reported as the main pollutants in the effluent discharged into the RIBS. Although the land application of wastewater ceased in 1995, the core of the plume remains anoxic, and its size and shape have not changed for at least 10 years (Repert et al., 2006; Savoie et al., 2006). This site shows that years of disposing treated effluent at high loading rates to a limited area may have irreversible negative impacts on groundwater.

Domestic and industrial wastewater usually contains a variety of organic compounds including pharmaceuticals, personal care products, and widely used household and industrial chemicals (Cordy et al., 2004; Conn et al., 2006; Aufdenkampe et al., 2006). Since these chemicals (i.e., emerging contaminants) can partially be removed by existing wastewater treatment technologies, they might reach the environment through surface water discharge or land application of the effluent (Conn et al., 2006). Some of the emerging contaminants have been found to be toxic and are persistent in the environment. For example, the antiepileptic drugs, carbamazapine and primidone, were detected in the groundwater after eight years of groundwater recharge by treated effluent (Drewes et al., 2003). Barbiturates and sedative hypnotics used in veterinary medicine, mostly during mid-1960s, have been detected in groundwater samples. Additional biotic and abiotic tests did not show any degradation either under aerobic conditions or hydrolysis, indicating that barbiturates may stay stable in the aquatic environment for decades (Peschka et al., 2006).

Purpose and Scope

The population of southern Delaware (2000 Census data) is projected to increase by 20 percent by 2020 (Delaware Population Consortium, 2006). This increase in population is accompanied by a rise in proposed residential subdivisions, including in southern New Castle, Kent, and Sussex Counties (Delaware Population Consortium, 2006). In Delaware, as in other states, many streams are subject to the EPA's Total Maximum Daily Load (TMDL) restrictions, which set a limit on the amount of a pollutant that can be discharged into a water body without compromising water quality. To meet water quality standards, communities must construct and operate effective wastewater treatment facilities.

The costs of constructing new or upgrading existing public wastewater treatment facilities can be daunting, especially for states with limited budgets. An increasing number of communities are implementing community-wide land-based disposal systems for treated wastewater. Delaware is one of many states that has become more receptive to privately funded and operated LBWD systems. With the need to meet TMDL restrictions and with budget concerns, many planned subdivisions have proposed RIBS for wastewater disposal.

In January 2006, the Delaware Department of Natural Resources and Environmental Control (DNREC) initiated new guidelines for designing and operating large LBWD systems including RIBS. Although RIBS have been used for wastewater disposal and groundwater recharge for the last 25 years, primarily in arid regions, they have been used less commonly in Delaware. Therefore, the performance of RIBS and the potential impacts of RIBS on the receiving environment are generally unknown for Delaware.

Groundwater is the most important natural source of fresh water in Delaware, with thirteen major aquifers providing more than 100 million gallons of water daily (Wheeler, 2003). Almost all of the fresh water used south of the Chesapeake and Delaware Canal is obtained from groundwater (Talley, 1985).

Groundwater is also the source of about 70 percent of fresh water stream flow (Johnston, 1976). Contamination is a major concern. More than 90 percent of the water bodies in Delaware are polluted, primarily with pathogens and nutrients from non-point sources that are extremely difficult to control (Denver et al., 2004; USEPA, 2002). Decades of inadequate agricultural and wastewater disposal practices have led to serious eutrophication problems in surface water. Poor agricultural and wastewater disposal have also led to serious groundwater contamination by NO_3^- (Miller, 1972; Robertson, 1977; Talley, 1985; Ritter and Chirnside, 1982, 1984; Andres, 1991, Hamilton et al., 1993; Denver et al., 2004).

The problems associated with groundwater contamination that are of primary concern vary by location. For example, three hydraulically connected aquifers, the Mt. Laurel, Rancocas, and Columbia, are major water sources for domestic and public wells in southern New Castle County. Groundwater contamination caused by the land application of wastewater in this region might adversely impact domestic or public wells in any or all of these aquifers. The connection between ground and surface water in the Inland Bays means that groundwater that becomes contaminated will eventually impact streams.

This work was designed to study the effects of RIBS on groundwater contamination in Delaware. The objectives of this study were to:

1. Evaluate the site selection criteria and performance of RIBS in the northeastern United States, including Delaware, and the wastewater treatment systems that may be used in conjunction with RIBS.
2. Review and compare existing DNREC permitted RIBS and associated wastewater treatment systems with their effluent data.
3. Review and compare operation and maintenance procedures used for other RIBS in the Mid-Atlantic States and identify key elements of operation and maintenance protocols for RIBS in Delaware.
4. Evaluate the performance of existing wastewater treatment systems in Delaware that may be used with RIBS.
5. Evaluate existing and planned RIBS sites for future field study.

The completion of these objectives was essential for addressing some of the questions regarding the siting, compliance, and pre-treatment requirements for RIBS.

A primary goal of this project was to provide scientific information to the DNREC so that they could improve existing guidelines and regulations for on-site wastewater treatment and disposal systems. To do this we evaluated the current practices for RIBS design, operation and maintenance, and environmental compliance monitoring as it is done in Delaware and then compared that information with equivalent information from nearby states.

Use of RIBS in Delaware

As of 2011, RIBS in Delaware are covered under *Regulations Governing the Design, Installation and Operation of Onsite Systems* (DNREC, 2004). However, very little specific information regarding the design and operation of RIBS is present in the regulations. Instead, specifics are covered in *Guidelines for Preparing Preliminary Groundwater Impact Assessments for Large On-site Wastewater Treatment and Disposal Systems* (State of Delaware, December 2005) and *Large System Siting, Design and Operation Guidelines* (DNREC, 2006). These guidelines are intended to minimize the impact of large systems such as trenches, beds, drip lines, sand mounds, and RIBS on the receiving environment (DNREC, 2006). According to the guidelines, if generated wastewater volume exceeds 20,000 gallons per day, it must be treated to meet secondary treatment standards, which require TN levels not to exceed 10 mg/L. Additionally, none of the disinfected wastewater being sent to any basin should exceed 200 col/100 ml of fecal coliform. Monthly average BOD and TSS concentrations in the effluent should not exceed 30 mg/L each.

However, some sites receive permits that allow the DNREC and the operator some leeway in meeting guidelines. For example, effluent from the Breeder's Crown wastewater treatment plant is allowed a limit of 25 mg/L of TN concentration because any site is subject only to the regulations stated in its existing permit, (Hilary Moore, DNREC, personal correspondence), which for Breeder's Crown is the Regulations Governing the Design, Installation and Operation of Onsite Systems (DNREC, 2004).

The guidelines do not recommend the addition of vegetation for RIBS; however, existing vegetation should be regularly maintained and grass cuttings removed from the basins. RIBS are required to be periodically scarified to remove any accumulated solids and organic materials that may clog the basin and lower the infiltration rate as part of routine maintenance. Details for RIBS maintenance are given in the guidelines (DNREC, 2006).

Treatment Practices Observed During This Study

Wastewater treatment plants using RIBS in Delaware employ five different secondary treatment processes. The most common is the rotating biological reactor (RBC). First introduced in 1960 in West Germany and nearly a decade later in the United States, RBCs introduce a biological medium into wastewater in order to remove pollutants prior to discharge. In an RBC, a series of closely spaced circular disks are 40 percent submerged in a tank containing wastewater. The plastic disks are typically 3.6 m in diameter and have a film of microorganisms growing on them. The disks are attached to a horizontal shaft that rotates slowly at about 1.0 to 1.6 revolutions per minute. As the RBC rotates, the microorganisms are periodically exposed to the atmosphere, providing aeration and facilitating the biological degradation of the pollutants by the microorganisms (Masters, 1998; Tchobanoglous and Stensel, 2003).

The second type of treatment process is termed activated sludge (AS), a suspended-culture system that has been in use since the early 1900s. The name derives from the settled sludge containing microorganisms that is returned to the reactor to increase biomass availability and accelerate the treatment reactions. In a conventional activated sludge process, raw or settled sewage flows into a large, concrete tank along with a mixed population of microorganisms. The mixture (mixed liquor) then enters an aeration tank, where it is combined with a large quantity of air, which accelerates the biological degradation of the wastes. After about 6 to 8 hours of aeration, the mixture flows into a large settling tank where the biomass slowly settles out of suspension and the flocculant microorganisms are removed from the effluent stream. Most of the settled microorganisms, or activated sludge, are then recycled to the head of the aeration tank to be remixed with wastewater. Because new activated sludge is continually being produced, some is removed or "wasted" from the process. The effluent from a properly designed and operated activated-sludge plant is of high quality, usually having BOD and TSS concentrations of equal to or less than 10 mg/L (Crites and Tchobanoglous, 1998).

The remaining treatment processes are all variations on the conventional AS process. The most common of these is the sequencing batch reactor (SBR). During the late 1950s and early 60s, improvements in equipment and technology led to an increased interest in SBRs in the United States. Enhanced aeration devices and computer control systems have made SBRs a more practical choice than conventional activated-sludge systems. Whereas a conventional system relies on multiple tanks or basins, the SBR equipment is a variation of the activated sludge process, and is unique in its ability to act as an equalization basin, aeration basin, and clarifier within a single reactor using a timed control sequence (Al-Rekabi et al., 2007; USEPA Office of Water, 2000).

SBRs are a set of tanks that operate individually on a fill-and-draw basis. Each tank has a cycle of five discrete time periods: Fill, React, Settle, Draw, and Idle. The tank is partially filled with biomass that has acclimated to the wastewater constituents during preceding cycles. Wastewater is allowed to enter the tank as Fill begins. Once the reactor is full, it behaves like a conventional activated sludge system, with the React, Settle and Draw portions of the cycle, but without a continuous influent or effluent flow. Aeration and mixing are discontinued after the biological reactions are complete, the biomass has settled, and the treated supernatant is removed. The period between Draw and Fill is termed Idle. Despite its name, this “idle” time can be used effectively to settle sludge (Barbato, 2006).

The extended aeration process (EA) is comparable to the conventional activated sludge process except that it operates in the endogenous respiration phase of the growth curve, which requires a low organic loading and long aeration time. Similarly, oxidation ditches (OD) typically operate in an extended aeration mode with long detention and solids retention times. OD originated in the Netherlands in 1954 and there are currently more than 9200 municipal oxidation ditch installations in the United States (USEPA, 2000). The oxidation ditch is a ring- or oval-shaped channel equipped with mechanical aeration devices. Screened wastewater enters the ditch, is aerated, and circulates at about 0.8 to 1.2 ft/s (0.25 to 0.35 m/s) to maintain the solids in suspension. When designed and operated for N removal, this process achieves nitrification to less than 1 mg/L NH_4^- -N The main advantage of the oxidation ditch is its low operational requirements, and operation and maintenance costs. However, compared to other modifications of the AS process, the concentrations of suspended solids in effluent associated with oxidation ditches are relatively high. Additionally, ODs require large land areas that may be costly (USEPA, 2000; Crites and Tchobanoglous, 1998).

The final type of treatment process is the Imhoff Tank (IT). Patented in 1906 and first used in Essen, Germany in 1908, the IT is one of the oldest and simplest treatment processes. The IT was developed to address the deficiencies of septic tanks by preventing the remixing of removed solids while promoting the decomposition of these solids within the same tank. In addition, the IT provides an effluent acceptable for further treatment. An IT is a two-story tank in which sedimentation takes place in the upper compartment and anaerobic digestion is accomplished in the lower compartment. Imhoff tanks are still used occasionally because they are simple to operate, there is no mechanical equipment to maintain, and they do not require highly skilled supervision (Crites and Tchobanoglous, 1998; Seeger, 1999).

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METHODS

The methods used in this study consist of two main parts. The first includes the literature search, site visits to the selected advanced wastewater treatment plants including RIBS, influent and effluent sampling, laboratory analyses, the collection of effluent quality data from nearby states, data processing, and the interpretation of these data. The second was the assessment of current RIBS regulations and operation and maintenance strategies.

Site Visits, Sampling, and Analysis

Permitting agencies in Delaware, New Jersey, Massachusetts, and North Carolina provided data on the types of treatment systems currently in use, reliability assessments of those systems, and quality monitoring of effluent and/or wells. The DNREC Non-Hazardous Waste Sites database provided data on the permitted flow, pretreatment method, effluent quality, and monitoring and inspection records on existing permitted RIBS in Delaware. We visited all nine of the operating RIBS in Delaware and three in New Jersey that were chosen based on their location, capacity, and treatment and discharge (e.g., RIBS discharge) methods. A list of treatment plants that we visited is given in Table 2.

We visited the 10 RIBS in summer 2007 to photograph the sites, interview the plant operators, and collect wastewater samples. Listed below are some of the questions that plant

Table 2. Advanced treatment plants vivisted in Delaware and New Jersey.

Facility	Treatment Type	Effluent Sampling Method	Capacity (GPD)	Location
Beaver Creek	SBR	24-hr Composite	81,600	DE/Sussex
Breeder's Crown Farm	RBC	Grab	18,600	DE/Kent
Cape Henlopen State Park	Imhoff Tanks	Grab	80,000	DE/Sussex
Colonial Estates	Activated Sludge	Grab	16,000	DE/Sussex
Heron Bay	SBR	Grab	50,000	DE/Sussex
Forest Grove	RBC	Grab	39,835	DE/Kent
Southwood Acres	RBC	Grab	51,914	DE/Kent
Stonewater Creek	SBR	24-hr Composite	225,000	DE/Sussex
West Bay Park	RBC	Grab	92,520	DE/Sussex
Hammonton	Oxidation Ditch	Not Sampled	1,600,000	NJ
Landis Sewerage Authority	Activated Sludge	Grab	12,200,000	NJ
Winslow	Oxidation Ditch	Grab	2,600,000	NJ

managers were asked:

- What type of treatment processes are used in this facility?
- What is the average daily flow rate of wastewater into the system?
- Is the plant operating at its design capacity?
- How long has the plant been in operation?
- What is currently being done with the treated effluent?
- What type of discharge method is used?
- How often are influent and effluent samples analyzed?
- What is done with wastewater sludge? Is it hauled or is it land applied?
- How is the quality of effluent in general?
- Is the effluent disinfected prior to RIBS application?
- If RIBS are used for effluent discharge, how many RIBS are there in the site?
- How long have the RIBS been in operation?
- What are the flooding/drying and RIBS rotation schedules?
- What type of maintenance do RIBS require (i.e. scoring, excavating, mowing, vegetation removal)?
- How is the vegetation on RIBS being taken care of? How often?
- Have you ever had any operational or maintenance problems? How did you solve them?
- Are there any monitoring or observation wells at the site? How many?

For wastewater sampling, duplicate 500 ml samples were placed into polyethylene bottles for both influent and effluent. On-site conductivity and pH measurements were performed with a portable AP50 pH/Ion/Conductivity instrument (Denver Instrument Company, Arvada, Colorado). Samples were immediately placed in ice and transported to the Water Quality Laboratory at the University of Delaware. Samples arrived at the laboratory within 2-3 hours of collection. A list of analyses done at the Water Quality Laboratory is given in Table 3.

Removal rates of N, P, BOD, COD and solids were calculated by using the analytical results of influent and effluent wastewater samples for the different treatment plants in Delaware. TN concentrations were calculated by adding the analytical results of Kjeldahl-N, NO_3^--N and nitrite-N. These results were used to evaluate the performance of the wastewater treatment technologies that are most commonly used or proposed for use in Delaware. To assess the level of compliance with generally accepted treatment standards (Tchobanoglous and Stensel, 2003), drinking water NO_3^- limits (USEPA, 2003), and Delaware Large System Regulations (DNREC, 2006) we determined exceedence frequencies for a total of 49 treatment plants in Delaware, New Jersey, North Carolina, and Massachusetts. Effluent quality data in DNREC's Non-Hazardous Waste Sites database (Hilary Moore, personal communication) combined with our analytical results were used to evaluate the exceedences. Each state's effluent data for different wastewater quality parameters including BOD, TSS, TN, NO_3^--N, and indicator organisms were used in the data analysis.

Comparison of State Regulations on Land Application of Wastewater

We also evaluated the siting criteria (depth to water table, presence or absence of restricting zones, proximity to wells and water bodies) and existing regulations or guidelines used in permitting and monitoring RIBS in Delaware and other states. Our comparison of state programs that regulate RIBS focuses on states that have generally similar climatic and hydrogeologic conditions. States with humid climates and aquifers hosted by unconsolidated to weakly consolidated sedimentary deposits were chosen. Despite an extensive internet research, only limited effluent data could be obtained from New York, Maryland, and Pennsylvania. Subsequent correspondence and telephone conversations with officials from these states yielded little additional information concerning current regulations with regards to RIBS. It is possible that there are other states for which we have not been able to locate the programs and regulations pertaining to RIBS.

Table 3. Wastewater analysis and analytical methods.

Parameter	Method	Comments
Biological oxygen demand (BOD)	SMWW[1] 5210B Winkler titration	% day BOD
Chemical oxygen demand (COD)	SMWW 5220D	Colorimetric
Total suspended solids (TSS)	SMWW2540 B, C, D, E	Gravimetric
Total dissolved solids (TDS)	SMWW2540 B, C, D, E	Gravimetric
Total Kjeldahl nitrogen (TKN)	SMWW4500C	Acid digestion
Nitrate-Nitrogen (NO_3-N)	SMWW4500 NH_4 B, C	Nitrate method
Ammonia-Nitrogen (NH_4-N)	SMWW4500 NH_4 B, C	Nitrate method
Ortho-Phosphorus (OP)	SMWW4500E	Colorimetric-ascorbic acid; Acid digestion
Dissolved Total-Phosphorus (TP)	SMWW4500E	Filtration; Colorimetric-ascorbic acid; Acid digestion
Total Coliform	SMWW9222D, 9230C	Membrane filtration

[1] Clesceri et al., 1998

RESULTS AND DISCUSSION

State Regulatory Programs and Technical Criteria

The regulatory approaches of states fit into a decision tree system. Sites are evaluated by multiple series of criteria, and the result of each evaluation step determines the next set of evaluation criteria. The categories of requirements these states use for RIBS compliance are summarized as follows.

- Buffer zone distances
- Effluent limits (BOD/TSS/TN/coliform)
- Pretreatment requirements
- Depth to water table
- Monitoring well requirements
- Storage capacity
- Flow rate

All states have certain criteria that must be met for RIBS to be allowed. These criteria include minimum setback requirements from property boundaries and wells, minimum depth to groundwater, and bodies of surface water (Figs. 1-6). Almost all states have the prerogative to evaluate each RIBS on a case by case basis.

Flow rate is a major factor in determining the specific design and operation requirements for RIBS. For example, Delaware and New Jersey use an expected effluent flow rate of 20,000 gpd to determine if primary rather than secondary treatment is needed before the effluent is discharged to the infiltration basins. It is following this step in the decision tree that states have the greatest differences in their regulatory requirements for the larger systems. These requirements fall into the categories of site exploration, effluent quality limitations, and effluent and groundwater monitoring.

USEPA guidance documents and several texts state that an unsaturated zone between the base of the infiltration basin and the water table is needed to allow for N removal from effluent (Crites and Tchobanoglous, 1998; Crites, et al., 2006; USEPA, 1985; USEPA, 1999). These documents explain that biogeochemical mediated reactions in the N removal process include mineralization or nitrification of organic N (to NH_4^-), sorption of NH_4^-, nitrification of NO_3^-, and denitrification. Increasing the thickness of the vadose zone provides a margin of safety to guard against N contamination of groundwater should effluent quality fail to meet regulations, guidelines, or permit requirements.

If the unsaturated zone is thin and the effluent contains substantial quantities of N, there is a significant risk that substantial amounts of N, in the forms of organic N, NH_4^-, or NO_3^- will reach the water table. These chemical constituents will travel down gradient with groundwater flow and will eventually discharge into a body of surface water or be pumped by a water supply well. To reduce this risk, USEPA documents recommend that the thickness of the vadose zone under RIBS must take into account the expected effluent quality (USEPA, 1985; USEPA, 1999), in addition to the expected water supply and the environmental uses of the shallow aquifer (USEPA, 2004).

States have reacted differently to USEPA guidance for determining the requirements for vadose zone thickness. Amongst the states with RIBS regulations that we surveyed, vadose zone thickness requirements range from as little as 2 ft (Delaware) to as much as 10 ft (Maryland). In no state, do the regulations contain explanations for how the distance requirements were determined; however, we assume that the requirements reflect a balance between the need for the wastewater treatment capacity to serve development and environmental protection, and the expected uses of the groundwater.

As of 2011, Delaware's *Large System Siting, Design and Operation Guidelines* requires only two ft of separation distance between a RIBS site and the water table; that is, there are two ft between the base of the infiltration bed and the mounded water table. Should the treated effluent not meet standards, further treatment by filtration and adsorption will be negligible in the small 2-ft distance to groundwater. As a result there is a significant risk of groundwater contamination in Delaware, especially in Sussex and Kent Counties where the water table is shallow.

The required separation distances between RIBS and environmentally sensitive receptors, such as wetlands, surface waters, and potable water supply wells are listed in the Delaware guidelines (Table 4). To minimize the risk of

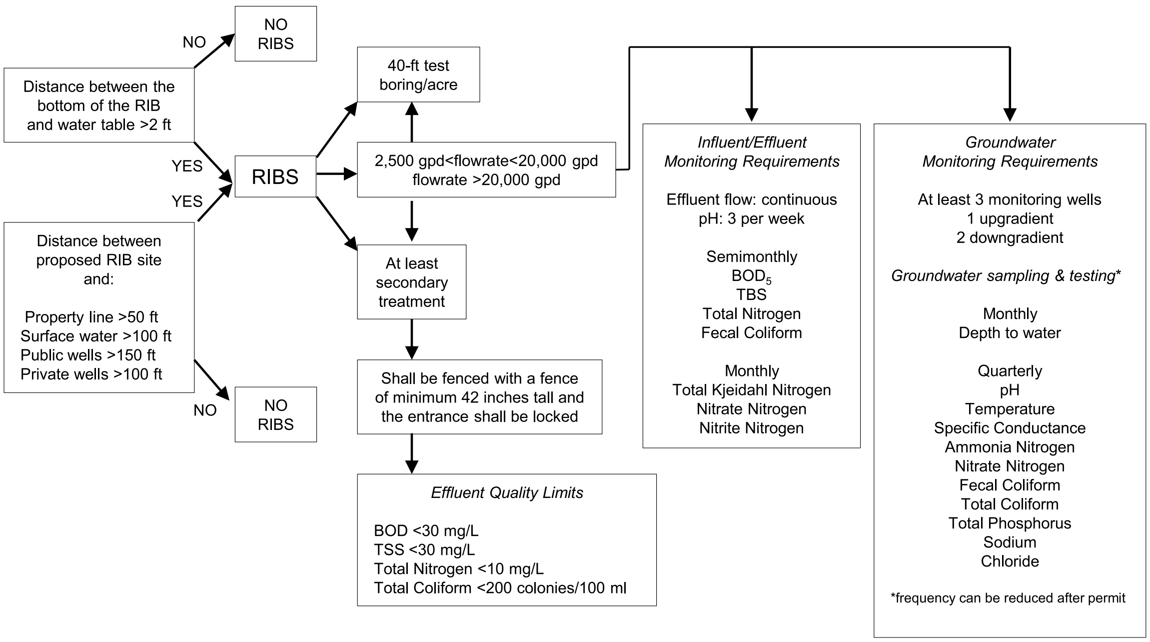

Figure 1. Decision tree illustrating regulations, major permitting criteria, and monitoring requirements for RIBS in Delaware (State of Delaware, 2005; DNREC, 2006).

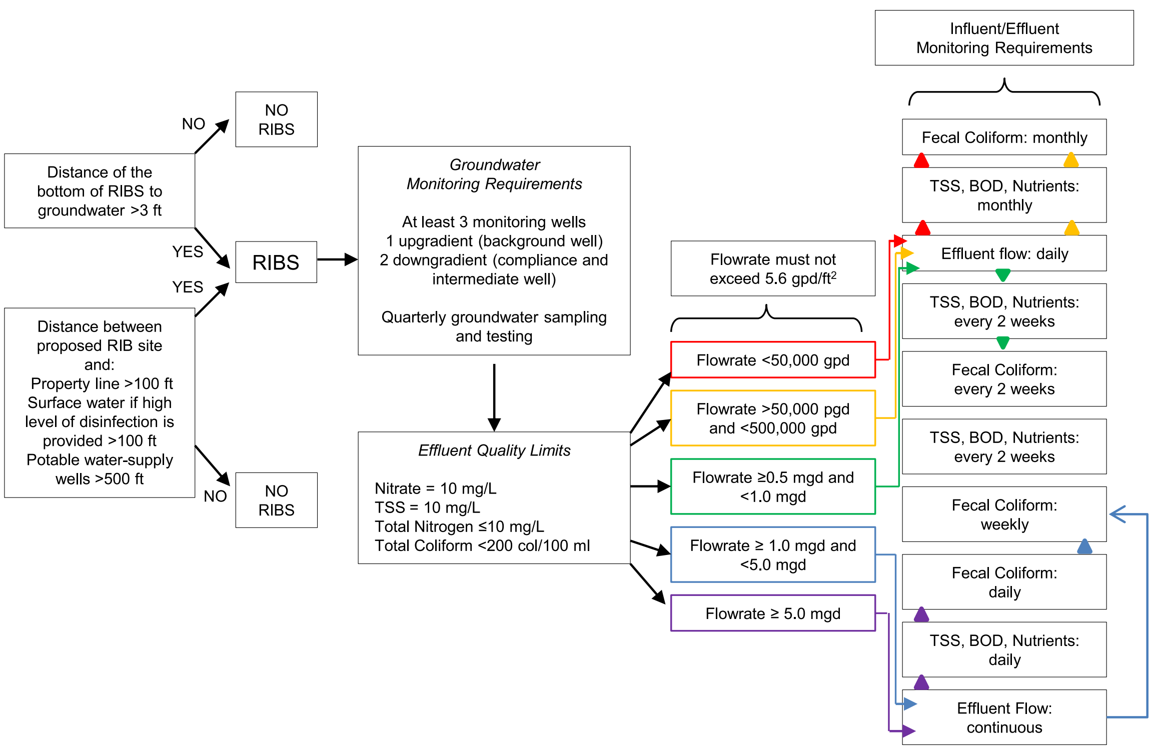

Figure 2. Decision tree illustrating regulations, major permitting criteria, and monitoring requirements for RIBS in Florida (Florida Department of Environmental Protection, 2005).

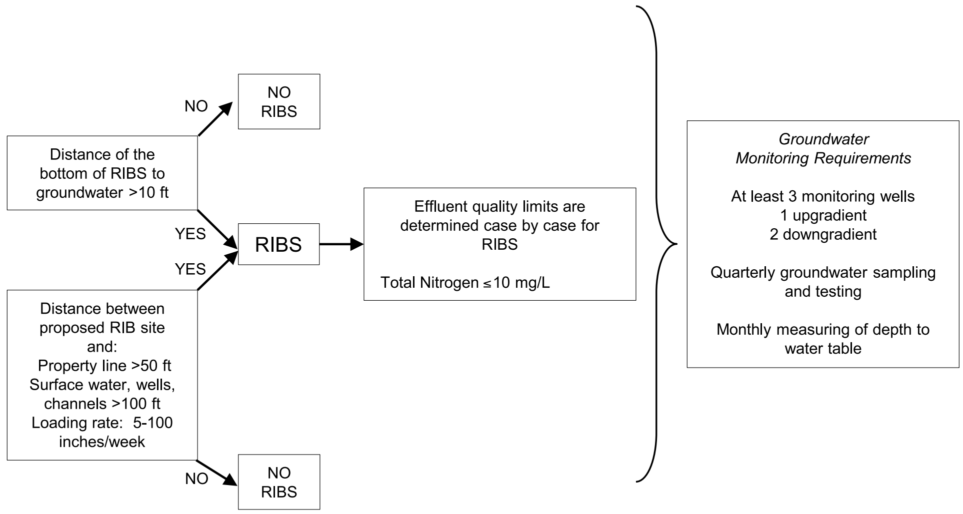

Figure 3. Decision tree illustrating regulations, major permitting criteria, and monitoring requirements for RIBS in Maryland (State of Maryland, 2003).

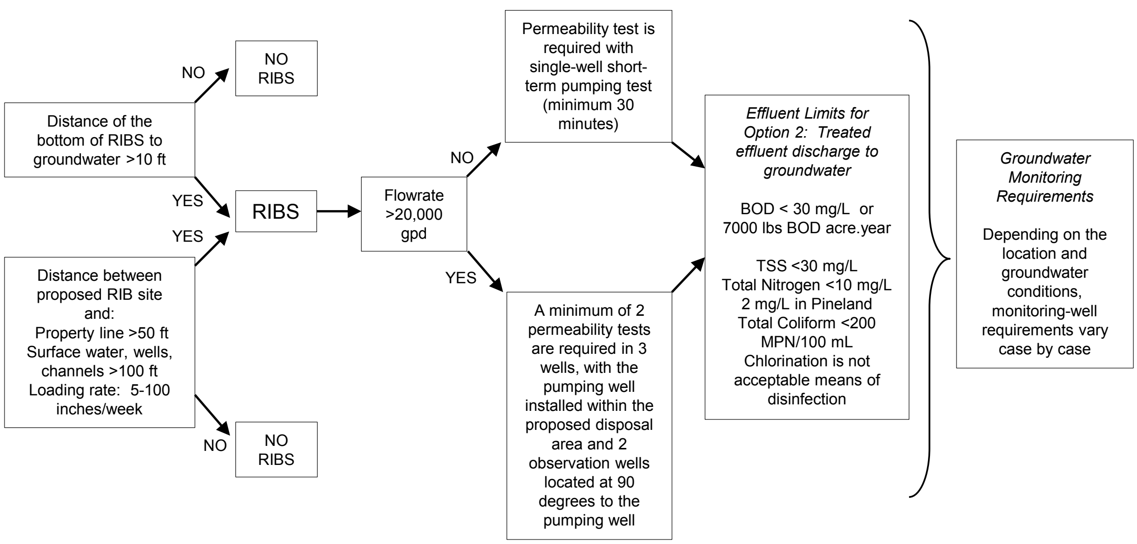

Figure 4. Decision tree illustrating regulations, major permitting criteria, and monitoring requirements for RIBS in New Jersey (State of New Jersey, 2002, 2005).

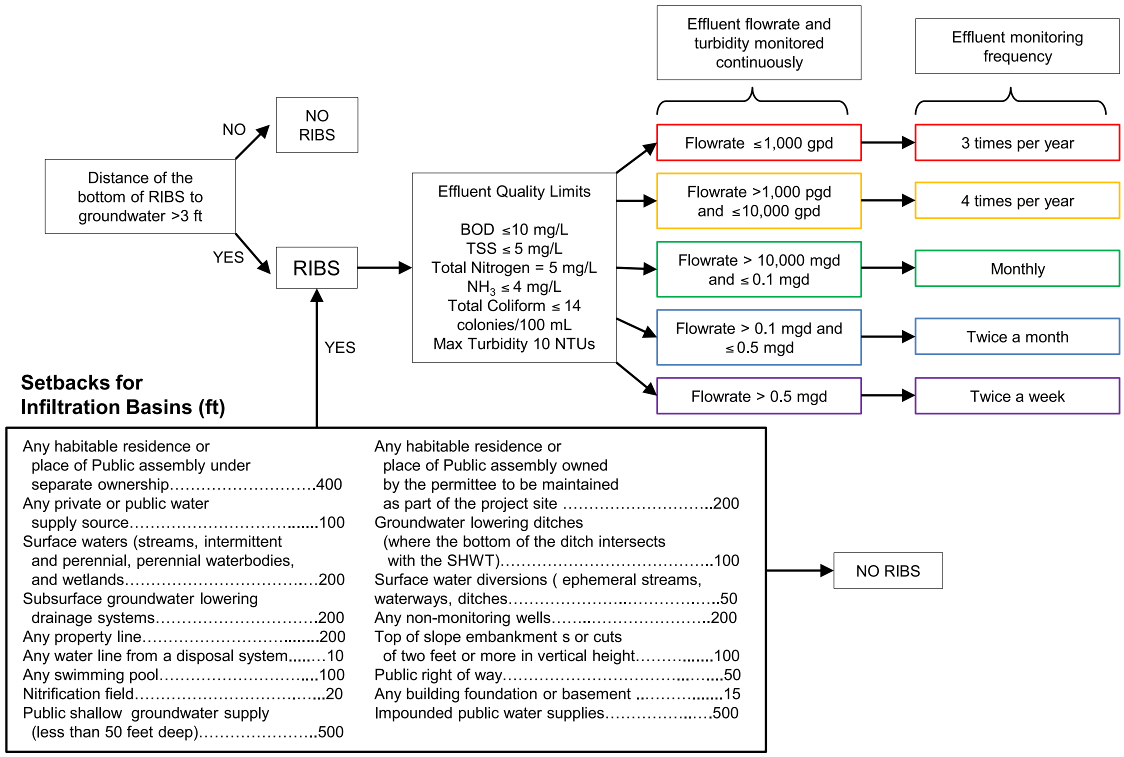

Figure 5. Decision tree illustrating regulations, major permitting criteria, and monitoring requirements for RIBS in North Carolina (State of North Carolina, 2006).

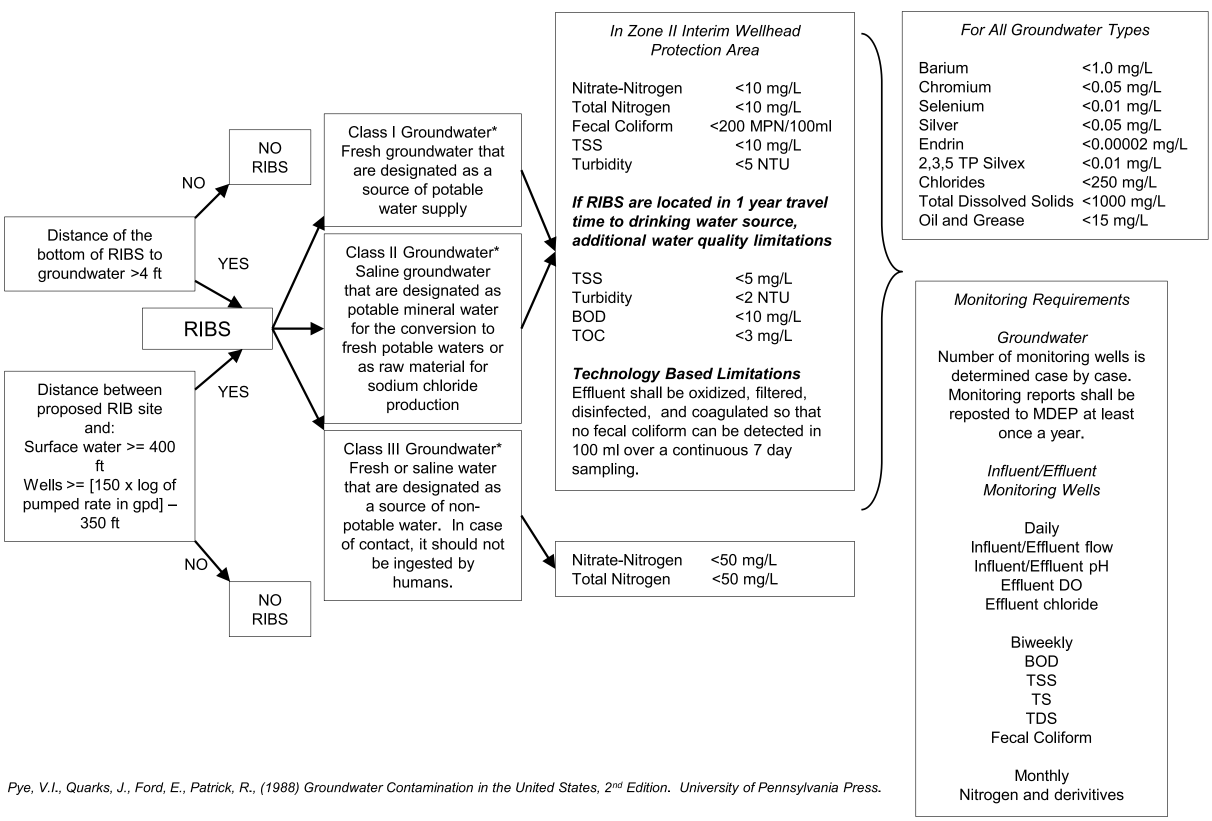

Figure 6. Decision tree illustrating regulations, major permitting criteria, and monitoring requirements for RIBS in Massachusetts (State of Massachusetts, 1984).

Table 4. Buffer distances for RIBS in Delaware and other states. Note that more stringent buffer distances may be required in some states according to flow rate.

Environmental Receptor	DE	MD	FL	NC	NJ	MA
Groundwater	2	10	3	4	4	4
Surface Water	100	100	100	200	200	100
Property Line	50	50	100	200	100	25
Public Well	150	100	500	100	400	400
Private Well	100	100	500	100	400	100

DNREC, 2006; Pye et al., 1988; State of Maryland, 2003; Sate of New Jersey, 2002; Florida Department of Environmental Protection, 2005; North Carolina Department of Environment and Natural Resources Division of Water Quality, 2006; State of Massachusetts, 1984.

contamination to sensitive receptors, many states require greater separation distances or use travel-time criteria based on site-specific hydrogeological conditions to determine an appropriate level of protection for each site. Interestingly, Delaware requires the use of travel-time criteria in its source water protection program.

North Carolina has a requirement that may be appropriate for Delaware. In some areas of the state, treatment plants must have additional wastewater storage in case the plant malfunctions or has a treatment upset. This requirement provides an extra margin of safety in areas where groundwater contamination caused by the discharge of poorly treated effluent poses a significant risk to sensitive receptors.

Effluent Characterization and Treatment Plant Performance - Delaware and New Jersey

Seven of the 10 treatment plants we visited were able to remove at least 90 percent of the biodegradable organic load from the influent wastewater using their existing advanced treatment processes (Fig. 7, Appendix 1). The analytical results of the influent/effluent samples taken from LSA and WTP were also included. Although three of the effluent BOD concentrations were close to the limit of 30 mg/L given in *Large System Siting, Design and Operation Guidelines*, only one of the treatment plants exceeded this requirement (DNREC, 2006). Treatment plants using the activated sludge process achieved the highest average BOD removal rates (98 percent), followed in decreasing order by OD, SBR, IT, and RBC. Most of these treatment plants are residential, small community treatment plants that primarily receive domestic wastewater. The high BOD removal efficiencies are evidence that most of the pollutants in this wastewater are easily biodegradable organic substances. Both New Jersey plants were able to reduce the BOD levels below the effluent BOD limit of 30 mg/L.

The removal rates for COD in influent and effluent wastewater samples are slightly lower than those for BOD (Fig. 8, Appendix 1). Almost complete COD removal was measured in both of the treatment plants in New Jersey. Although not stated in the guidelines, 40-100 mg/L COD effluent is usually considered acceptable for the land application of wastewater (Tchobanoglous and Stensel, 2003). The effluent COD concentrations of 2 of the 10 treatment plants exceeded the concentration range given above. However, since the BOD concentrations in the wastewater of these plants were well below the guideline limits, we conclude that some of the organic matter was resistant to biodegradation and could only be degraded chemically, which required more oxygen.

Only 1 out of 10 effluent samples were measured at well above the TSS guideline of 30 mg/L for both Delaware and New Jersey (DNREC, 2006; State of New Jersey, 2002) (Fig. 9, Appendix 1). The highest TSS concentration of 112 mg/L was measured in the effluent of Forest Grove Wastewater Treatment Plant, which uses RBC as the main biological treatment process. During our visit to Forest Grove (FG) in July 2007, we observed solids floating at the surface of the secondary clarification tank. The high con-

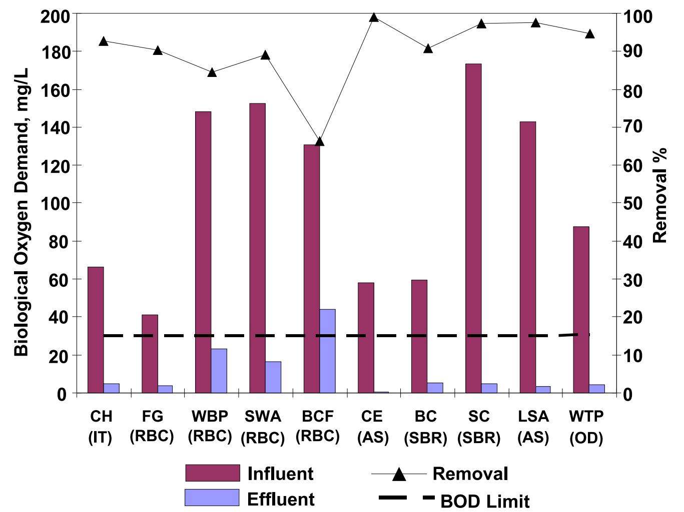

Figure 7. Concentrations of biological oxygen demand in the influent and effluent samples from different wastewater treatment plants and percent removal rates. Facility abbreviations are listed in the front of this report.

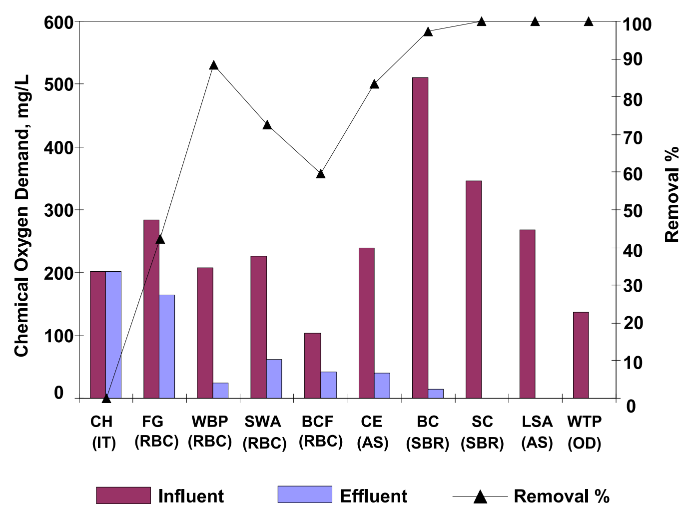

Figure 8. Concentrations of chemical oxygen demand in the influent and effluent samples from different wastewater treatment plants and percent removal rates. Facility abbreviations are listed in the front of this report.

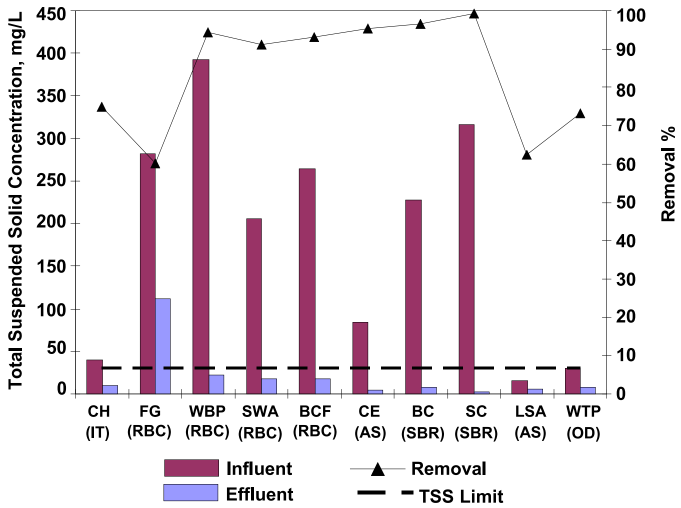

Figure 9. Total suspended solids concentrations in the influent and effluent samples from different wastewater treatment plants and percent removal rates. Facility abbreviations are listed in the front of this report.

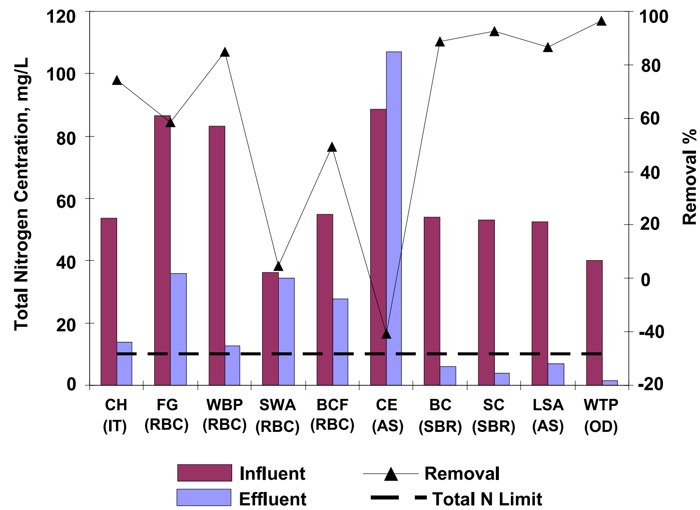

Figure 10. Concentrations of total nitrogen in the influent and effluent samples from different wastewater treatment plants and percent removal rates. Facility abbreviations are listed at the front of this report.

centration of solids in the effluent is thought to be the result of ongoing denitrification at the bottom of the clarification tanks due to the anoxic conditions. As denitrification produces N gas, it rises to the surface and resuspends settled solids. High concentrations of solids were reported in the treatment plants that used the same tanks for biological treatment and nutrient removal with insufficient aeration. These results showed that the SBR process is the most efficient in TSS removal.

Seasonal temperature differences might also play an important role in TSS concentration. Despite its state-of-the-art design and operation and low TSS concentrations, Landis Sewerage Authority (LSA) in Vineland, New Jersey, exhibits algae growth problems in its chlorine contact/equalization tanks during the summer months (Dennis Palmer, LSA, personal communication). Since algae increase the concentration of solids, to prevent clogging of the RIBS from April through October, the effluent is used only for spray irrigation. This type of algae problem was not observed in any of the treatment plants that we visited in Delaware.

When the N removal efficiency of different treatment processes were compared, SBRs were found to be the most efficient (Fig. 10, Appendix 1). Only 2 of the 8 treatment plants in Delaware met the effluent TN requirement, which is listed as 10 mg/L in the guidelines (DNREC, 2006). However, among the sites we visited, only four of the eight treatment plants (BC, SC, SWA and WBP) have a nutrient reduction process.

According to our results, conventional secondary wastewater treatment is inadequate for nutrient removal. The higher N concentrations in the effluent of the Colonial Estates Treatment Plant were due to incomplete N removal, resulting in an increase in the NH_4^- concentration as a by-product. This suggests that the oxidation of NH_4^- to NO_3^- is not complete due to the lack of dissolved oxygen caused by insufficient aeration in the system. High dissolved oxygen concentrations during aeration also lead to a reduction in excess sludge production (Kulikowska et al., 2007). The

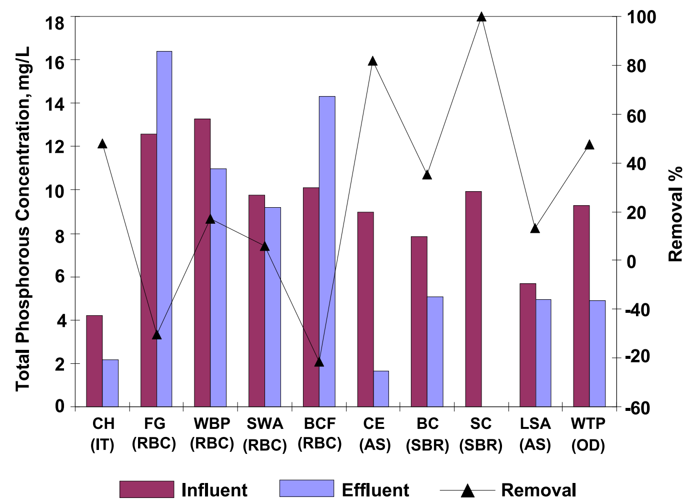

Figure 11. Total phosphorus concentrations in the influent and effluent samples from different wastewater treatment plants and percent removal rates. Facility abbreviations are listed in the front of this report.

better performance of SBR processes in overall nutrient removal is primarily due to the intermittent oxygen supply, which provides aerobic and anoxic conditions for complete N removal. Since the nutrients are concentrated in the sludge, the timely removal of excess sludge from the system prevents N and P from solubilizing back into the water (Tchobanoglous and Stensel, 2003).

The removal rates of TP were significantly lower than those of any of the other parameters. As mentioned previously, P removal is directly related to the N removal efficiency of a treatment process. Despite being lower, the P removal performances of the treatment plants exhibited trends similar to the N removal trends (Fig. 11, Appendix 1). Interestingly, in FG and Breeder's Crown Farm (BCF) the P concentrations were higher in the effluent samples than in the influent samples. Since P removing bacteria release extracellular P into the system and

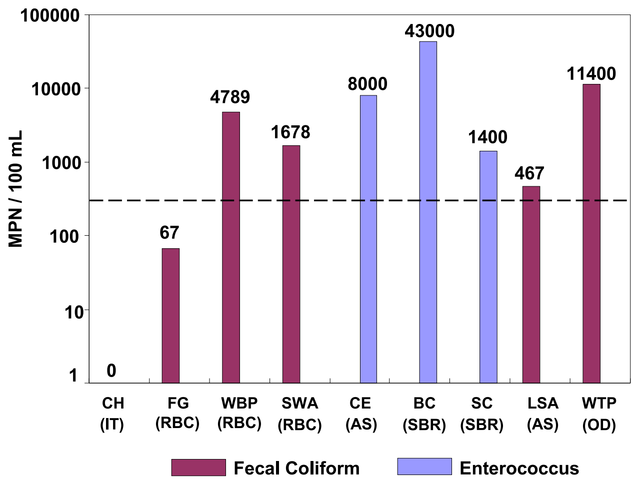

Figure 12. Indicator organism concentrations in the effluent samples. Facility abbreviations are listed at the front of this report. Dashed line is the guideline limit 200 colonies/100mL. MPN is Most Probable Number

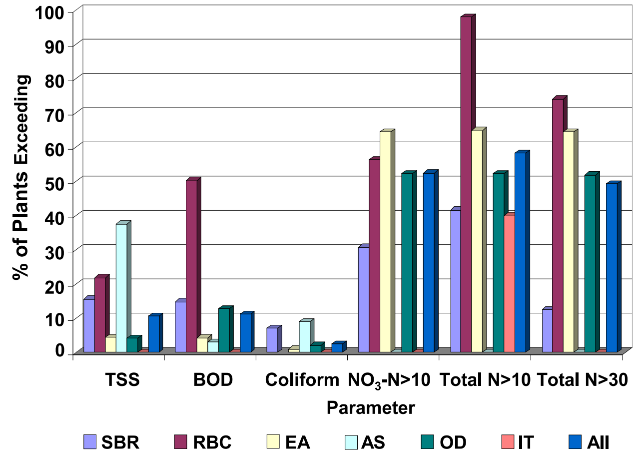

Figure 13. Comparison of parameter exceedences based on treatment processes.

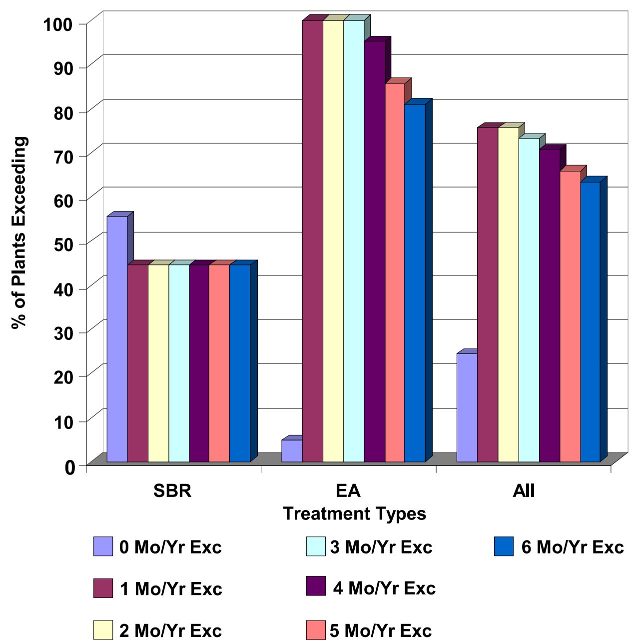

Figure 14. Comparison of frequencies of nitrate exceedences.

then uptake more than they released, higher P concentrations in the effluent indicate incomplete P removal. Overall, the poor nutrient removal performance of the treatment plants was strongly correlated with the RBC units that are used as the main biological treatment process. The highest P removal (100 percent) was observed at Stonewater Creek Treatment Plant, which utilizes a SBR system.

The Delaware guidelines state that all wastewater should undergo disinfection, preferably by ultraviolet, prior to being sent to the infiltration basins (DNREC, 2006). Disinfection must bring the fecal coliform concentration below 200 colonies/100 mL. In the wastewater treatment plants we sampled, we found indicator organism concentrations above the limits in a majority of the effluent samples (Fig. 12, Appendix 1). We anticipated this result since the Cape Henlopen State Park Wastewater Treatment Plant is the only site that disinfects the treated effluent prior to RIBS discharge. Up to 100 percent virus or bacteria removal might be achieved via filtration, especially in areas where the water table is deep. However, groundwater is more susceptible to microbiological contamination when the water level is close to the land surface as is the case in southern Delaware (Martin and Andres, 2008). Therefore, the proper pre-treatment and disinfection of wastewater prior to RIBS discharge is particularly important for Delaware.

Effluent Characterization and Treatment Plant Performance - All States

The treatment types, effluent quality parameters, and percent exceedences from the wastewater treatment plants of four states are shown in Appendix 2, and the results are illustrated in Figures 13 and 14.

An analysis of the N data is complicated by differences in the analytical schedules, sampling frequencies, and effluent quality requirements. For example, some of the treatment plants in Delaware are still subject to a 25 mg/L TN effluent limit; as a result, NO_3^- was not measured as frequently as TN. Conversely, TN was not measured for EA plants in North Carolina. We have aggregated the data using the following assumption: TN is set equal to NO_3^- for North Carolina plants that use EA and OD treatment processes and for SBR plants in other states that report only NO_3^- concentrations. The effect of this assumption is that a plant exceeding a 10 mg/L NO_3^--N limit will also exceed a 10 mg/L TN limit. There is the possibility of a false negative if an EA or OD plant that is experiencing treatment upset discharges poorly treated effluent with high TN but little NO_3^-.

The EA process is used in 24 of 49 evaluated treatment plants; most are located in North Carolina. Compared with the other treatment methods, EA has the highest representation in the analyzed data (Fig. 13). Although most of the EA data sets did not include TN values, more than three-fourths of those that did exceeded the 10 mg/L NO_3^--N limit in multiple months per year (Fig. 14). This is expected because a conventional EA process increases the oxidation of NH_4^- to NO_3^- in the influent but does not include a denitrification step prior to discharge. Given that EA plants consistently fail to meet NO_3^- standards, they pose a significant risk of causing high NO_3^- concentrations in groundwater, especially in areas with a shallow (<10 ft) depth to groundwater. Less than 5 percent of the treatment plants using the EA process exceeded the TSS, coliform, and BOD limits, indicating the effectiveness of sufficient aeration for the removal of organics and suspended solids.

Eleven treatment plants using SBR were evaluated. These facilities behave similarly to EA facilities (Fig. 13), although the percent limit exceedences for TSS, BOD and total coliform were higher for SBR plants than EA plants. Compared to RBC, EA, and OD, the intermittent oxygen supply in the SBR process leads to a lower but still significant occurrence of limit exceedence for NO_3^-. SBR plants do not exceed a TN limit of 30 mg/L. Although the SBR process appears to be more efficient than other processes in NO_3^- and TN removal, the data indicate that SBR plants do not consistently meet the NO_3^- standard (Fig. 14). This is a concern for Delaware, where NO_3^- contamination of groundwater poses risks to sensitive receptors.

Less than 10 percent of the total number of treatment plants studied exceeded the limits for TSS, BOD and total coliform limits. Nearly three-fourths of the plants exceeded the effluent NO_3^- limits in at least one month per year, and a significant proportion of the EA and SBR plants exceeded the NO_3^- limit in more than six months per year (Fig. 14). As expected, TN (10 mg/L limit) was the second most exceeded effluent quality parameter. When the TN limit is increased to 30 mg/L, the overall exceedence percentage decreased slightly more than two times. The long-term effects of NO_3^- and TN exceedence on groundwater quality and the sensitive receptors down flow of the RIBS that receive poorly treated effluent need to be investigated further.

Five treatment plants used oxidation ditches (OD), three in North Carolina and two in New Jersey. Despite not having TSS and BOD records for the Winslow and Hammonton (New Jersey) WWTPs, an analysis of the existing data showed that the exceedences of the percent TSS and BOD limits in OD plants are lower than those of RBC and SBR plants. Similar to EA sites, the majority of OD sites do not have records for TN and so the TN exceedence percentages for both EA and OD sites may not represent the actual results. The total coliform exceedence of OD sites is the second lowest among all the treatment processes. As mentioned earlier, since microorganisms tend to attach to the small solid particles in the wastewater, the efficient removal of solids results in better removal of pathogens.

The rotating biological contactor (RBC) process is used in 4 of the 49 treatment plants evaluated, all of them located in Delaware. Treatment plants with the RBC process have very high exceedence limits for NO_3^-, BOD, and TN (Fig. 13). These results agree with our laboratory analyses of effluent samples taken from treatment plants with RBCs. As mentioned before, during our site visits, we observed that RBC sites had lower treatment performances when compared to other treatment processes. Since DNREC's Non-Hazardous Waste Sites database does not have total coliform records for the treatment plants evaluated in this project, none of the RBC sites have effluent coliform records. However, effluent sample results from this study showed that all four RBC sites in Delaware have effluents with pathogen concentrations above the guideline limits of 200 colonies/ 100 mL. Should the RIBS have hydraulic problems and prolonged periods in which effluent ponded in the RIBS, this would be an immediate health risk.

The three treatment plants that use the activated sludge (AS) process were also evaluated. However, one treatment plant in Delaware does not have any records of analyses of NO_3^-, total coliform, or total N and so the only information on effluent quality for this plant is from the samples that were taken during our site visit. This dataset shows that facilities with AS have the highest TSS percent limit exceedences. One of the most common reasons for high TSS problems in biological treatment units, especially in clarifiers, is called "sludge rising" (Tchobanoglous and Stensel, 2003). Anoxic conditions in the settled sludge layer trigger denitrification, which can lead to the sludge layer becoming buoyant and floating to the surface along with N gas. Increasing the frequency of sludge collection tends to reduce the sludge detention time in the clarifiers, and can help to reduce TSS problems. Another probable reason for low effluent quality in AS plants is foaming, which is caused by certain types of filamentous bacteria, particularly *Microthrix parvicella* and *Nocardia* (Tchobanoglous and Stensel, 2003). Since these organisms are hydrophobic, they attach to and therefore stabilize air bubbles, which cause foam formation. Spraying chlorine on the foaming surface, reducing the oil and grease content in the wastewater, and adding cationic polymers are some of the common solutions used to prevent foaming.

The only treatment plant with an IT process that was evaluated is located in Cape Henlopen State Park in Delaware. This treatment plant was built in 1941, upgraded in the early 1980s, and has had operational RIBS since 1983. The performance of this IT plant was evaluated based on the laboratory test results of influent/effluent samples taken from the treatment plant and the effluent quality records obtained from DNREC. TN was the only parameter that was exceeded. Unlike other treatment facilities that we visited in Delaware, this site disinfects the treated effluent prior to RIBS discharge. Disinfection with chlorine gas lowers the total coliform concentration to below guideline limits of 200 colonies/100 mL.

CONCLUSIONS AND RECOMMENDATIONS

Although RIBS technology has the potential to be a beneficial alternative to surface discharge and a means for groundwater recharge, RIBS is appropriate only if the adverse environmental impacts are minimized. Because of the costs associated with remediating or mitigating the problems that result from poor management of WWTFs, regulations, policies, and guidelines should be stringent enough to protect public and environmental health from the possible impacts of RIBS. Establishing good policies not only improves the decision making process during permit application and review, but also minimizes the short and long term impacts of RIBS on the receiving environment.

The most common and serious problems associated with treatment plants located in Delaware and neighboring states are high nutrient and pathogen concentrations in the effluent. Years of application of treated effluent with high nutrient, pathogen, and organic content to RIBS will result in significant risks for the environment and public health. Although a simple disinfection unit can remove pathogens from effluent, reducing high nutrient concentrations below regulatory limits may require modifying treatment processes or upgrading treatment plants, steps that are much more significant and costly. Considering the high costs associated with fixing treatment plants, additional permitting safeguards are needed to limit the risks of serious widespread groundwater contamination that result from poorly performing WWTPs.

In Delaware, the discharge of poorly treated effluent to RIBS creates a risk of nutrient and pathogen contamination in the receiving water body, the shallow Columbia aquifer. The risk of serious groundwater contamination is most significant where the water table is shallow, as it is over much of Sussex and Kent Counties. In these locations, effluent discharged into RIBS undergoes much less additional treatment before reaching the water table. The risk of serious groundwater contamination in areas with a deep water table is unknown. Because the Columbia aquifer serves as a major source of potable water and stream flow in this region, site selection for RIBS must take into account the potential for damage to this resource. In cases where the depth to groundwater and the distance from sensitive receptors are adequate, RIBS design, construction, and operation must minimize the risk of groundwater contamination.

The 3-ft thickness required in Florida reflects that state's significant investment in water reclamation to serve irrigation users and to control salt water intrusion from sea level canals (USEPA, 2004). The 3-ft thickness rule used in New Jersey in part reflects the use of RIBS to augment and manage the quality of baseflow in streams draining the Pinelands, where a majority of the RIBS are located. Furthermore, several of the larger RIBS in New Jersey have replaced the direct surface water discharge that had impaired water quality and habitats. The 10-ft depth to ground-water rule in Maryland reflects the need to maintain water quality in the shallow aquifer, which is a significant source of potable water as well as the primary source of streamflow. These concerns are similar to those in Delaware.

The control of N in wastewater effluent is of special concern in Delaware. NO_3^- contamination of shallow groundwater has been a significant problem over large areas of Delaware and Delmarva for decades (Denver et al., 2004; Miller, 1972; Robertson, 1977; Ritter and Chirnside, 1982; Bachman, 1984; Andres, 1992). These studies have documented that oxic conditions in the shallow aquifer favor the persistence and transport of NO_3^- over great distances (kilometers) and time scales (decades). Many additional studies, including Andres, 1992; Hamilton et al., 1993; Pellerito et al., 2006; and Bachman and Ferrari, 1995, have documented that NO_3^- has led to the contamination of domestic and public water supply wells and significantly contributes to the eutrophication of many surface water bodies.

Nearly four decades of research have shown that the infiltration of water containing high concentrations of TN and/or NO_3^- into the ground creates conditions in which groundwater contamination by NO_3^- is certain, and contamination by other compounds is a significant risk. We strongly recommend that additional treatment, engineering, operational, and siting controls be used with RIBS to limit the discharge of NO_3^- and other contaminants into the water table. For example, a greater separation distance between the base of the infiltration basins and the mounded water table, similar to Maryland's 10-ft requirement, is a simple way to limit the discharge of NO_3^- and TN to groundwater. As seen in other states, combinations of redundant engineering controls on the quality of effluent discharged to the ground, and advanced effluent and groundwater monitoring can reduce the risks of contamination and thus substitute for a portion of the separation distance. We also recommend that the fixed buffer distances between RIBS and streams and wells be more rigorously defined to account for disposal rate, engineering controls, and the site specific characteristics of the aquifer. This last concept is similar to that used in the Source Water Protection Program.

P impacts on groundwater due to RIBS have not been specifically studied in Delaware. Because proposed TMDLs in Delaware have P requirements, and P in groundwater will eventually reach streams, this issue warrants further attention.

At this time, no regulations have been specifically developed for RIBS, and as a result there have been a variety of approaches to RIBS design and site characterization taken by permit applicants. Regulations developed from a technically-based assessment of RIBS in the region and a consideration of Delaware-specific hydrogeological and water resources issues is needed to provide the state with clear and consistent expectations for RIBS siting, design, and performance. In turn, regulations would help the designers, operators, and owners of RIBS to provide wastewater disposal systems that are environmentally sound and that protect public health.

Our evaluation of the wastewater treatment sites we visited and the treated effluent data showed that overall operation and maintenance practices play important roles in the performance of treatment plants. The most efficiently working WWTPs are usually the ones with good management. Conversely, the plants with fewer or part-time personnel, apparent safety hazards, and visible problems with the treatment units (i.e. solids floating in the tanks, foaming) have lower treatment efficiencies and a greater number of problems with functioning of the RIBS.

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APPENDIX 1. Analytical results of influent and effluent samples from selected wastewater treatment plants in Delaware.

Facility	Design Flow (gpd)	Current Flow (gpd)	NH_4^--N ppm		NO_3^--N ppm		TKN ppm		Total N ppm		OP ppm	
			Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
Cape Henlopen	80,000	75,000	48.328	10.161	0.78	2.15	52.85	11.71	53.64	13.86	4.096	1.085
Forest Grove	39,835	5,000	42.504	5.081	39.76	35.36	46.65	0.43	86.41	35.79	8.012	8.316
West Bay Park	92,520	17,000	67.535	5.824	0.29	9.46	82.84	3.16	83.13	12.62	8.882	7.121
South Wood Acres	51,914	8,500	41.388	4.213	0.54	26.44	35.50	7.87	36.04	34.30	5.232	5.093
Breeder's Crown Farm	18,900	6,000	28.377	9.542	26.50	19.99	28.32	7.87	54.82	27.86	7.030	8.027
Colonial Estates	16,000	7,000	48.328	0.000	0.60	39.84	88.04	67.10	88.64	106.94	0.101	0.034
Beaver Creek	81,600	8,000	55.453	0.248	1.22	2.42	55.45	3.66	54.07	6.07	0.160	0.079
Stonewater Creek	225,000	11,000	47.089	0.867	0.47	0.81	47.09	3.16	52.94	3.96	0.134	0.008

Facility	TP ppm		TSS mg/L		TDS mg/L		COD mg/L		BOD mg/L		Fecal Coliform
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Effluent
Cape Henlopen	4.195	2.184	40	10	72	73	202	202	66	5	0
Forest Grove	12.579	16.411	282	112	39	49	284	164	41	4	67
West Bay Park	13.255	10.986	392	22	48	36	208	24	148	23	4789
South Wood Acres	9.779	9.196	206	18	52	50	226	62	153	17	1678
Breeder's Crown Farm	10.103	14.308	264	18	45	53	104	42	131	44	
Colonial Estates	8.976	1.637	84	4	122	213	240	40	58	1	8000
Beaver Creek	7.868	5.096	228	8	38	40	510	14	60	6	43000
Stonewater Creek	9.941	0.000	316	2	43	32	346	0	173	5	1400

Note: gpd - gallons per day, ppm - parts per million, mg/L - milligrams per liter, ND - not detected, NH_4^--N - Ammonia Nitrogen, NO_3^--N - Nitrate Nitrogen, TKN - Total Kjeldahl Nitrogen, Total N - Total Nitrogen = TKN + NO_3^--N, OP - Ortho-Phosphate, TP - Total Phosphorus, TSS - Total Suspended Solids, TDS - Total Dissolved Solids, COD - Chemical Oxygen Demand, BOD - Biological Oxygen Demand, Fecal Coliform - colonies per 100 milliliters.
Design flow is from DNREC files and current flow reported by operator on date of visit.

APPENDIX 2. List of treatment facilities evaluated in this study and their percent exceedences of effluent quality limits. Exceedences of BOD (30 mg/L), and suspended solids (30 mg/L) in effluent are determined relative to concentrations expected from secondary treatment (Tchobanoglous Stensel, 2003, p. 8), for total nitrogen (30 mg/L) relative to concentrations expected from tertiary wastewater treatment (Tchobanoglous, and Stensel, 2003, p. 1377) and for nitrate-nitrogen (10 mg/L) relative to the USEPA standard for drinking water (USEPA, 2003) and DNREC (2006). Results are significant for evaluating risk of groundwater contamination in Delaware's hydrogeologic setting, but do not indicate compliance or lack of compliance with state regulations or specific permits.

				Total Suspended Solids		Nitrate		Biochemical Oxygen Demand		Total Coliform		Total Nitrogen (>10mg/L)		Total Nitrogen (>30mg/L)	
NonHazID/ Permit ID	**Name**	**State**	**Type**	**# Months Exceed**	**% Months Exceed**	**# Months Exceed**	**% Months Exceed**	**# Months Exceed**	**% Months Exceed**	**# Months Exceed**	**% Months Exceed**	**# Months Exceed**	**% Month s Exceed**	**# Months Exceed**	**% Months Exceed**
19	Bethany Bay	DE	SBR	2	9.52	8	61.54	2	10.00	no data	no data	13	59.09	4	18.18
27	Cape Henlopen	DE	IT	0.00	0.00	0.00	0.00	0	0.00	0	0.00	2	40.00	0	0.00
193	Colonial Estates	DE	AS	2	40.00	no data	no data	0	0.00	no data	no data	no data	no data	no data	no data
218	Forest Grove MHP	DE	RBC	4	16.67	no data	no data	15	62.50	no data	no data	11	100.00	11	100.00
261	South Wood Acres	DE	RBC	12	40.00	1	20.00	19	63.33	no data	no data	8	100.00	5	62.50
268	Breeder's Crown	DE	RBC	0	0.00	4	80.00	3	60.00	no data	no data	5	100.00	4	80.00
284	Stonewater Creek	DE	SBR	0	0.00	12	54.55	0	0.00	no data	no data	14	63.64	2	9.09
285	Heron Bay	DE	SBR	0	0.00	3	75.00	0	0.00	no data	no data	5	100.00	0	0.00
297	Beaver Creek	DE	SBR	0	0.00	0	0.00	0	0.00	no data	no data	3	37.50	0	0.00
336	West Bay Park	DE	RBC	4	30.77	9	69.23	2	15.38	no data	no data	12	92.31	7	53.85
370	Mobile Gardens MHP	DE	Septic	6	46.15	no data	no data	5	38.46	no data	no data	4	100.00	0	0.00
21	Barnstable WWTP	MA	AS	8	72.73	0	0.00	1	9.09	2	18.18	0	0.00	0	0.00
24	Edgartown WWTF	MA	EATF	1	9.09	0	0.00	0.00	0.00	0	0.00	1	9.09	0	0.00
200	Surfside	MA	SBR	6	54.55	no data	no data	8	72.73	no data	no data	no data	no data	no data	no data
201	Siasconset WWTP	MA	SBR	0	0.00	0	0.00	1	8.33	0	0.00	0	0.00	0	0.00
656	Town of Acton WWTF	MA	SBR	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
657	Devens WWTF	MA	SBR	0	0.00	0	0.00	0	0.00	2	18.18	0	0.00	0	0.00
677	Town of Plymouth WWTF	MA	SBR	7	58.33	0	0.00	6	50.00	0	0.00	2	28.57	0	0.00
WQ0000165	Sands Villas	NC	SBR	0	0.00	6	85.71	1	1.79	1	1.82	-	-	-	-

RBC	Rotating Biological Contactor	4	**IT**	Imhoff Tank	1	**AS**	Activated Sludge	3
SBR	Sequencing Bach Reactor	11	**OD**	Oxidation Ditch	5	**EATF**	Extended Aeration	24

APPENDIX 2. List of treatment facilities evaluated in this study and their percent exceedences of effluent quality limits (continued).

				Total Suspended Solids		Nitrate		Biochemical Oxygen Demand		Total Coliform		Total Nitrogen (>10mg/L)		Total Nitrogen (>30mg/L)	
NonHazID/ Permit ID	Name	State	Type	# Months Exceed	% Months Exceed	# Months Exceed	% Months Exceed	# Months Exceed	% Months Exceed	# Months Exceed	% Months Exceed	# Months Exceed	% Month s Exceed	# Months Exceed	% Months Exceed
WQ0000224	Point Emerald Villas WWTF	NC	EATF	2	3.57	6	60.00	1	1.79	0	0.00	-	-	-	-
WQ0000889	PCS Phosphate Co-Onsite Fac	NC	OD	0	0.00	11	73.33	0	0.00	0	0.00	-	-	-	-
WQ0000910	The Village at Nags Head	NC	EATF	2	3.70	5	45.45	0	0.00	0	0.00	-	-	-	-
WQ0000986	Island Beach & Racquet Club Condos	NC	EATF	9	16.07	34	94.44	19	34.55	0	0.00	-	-	-	-
WQ0002042	Clarion Hotel-Nags Head Beach	NC	EATF	0	0.00	2	28.57	2	4.00	1	2.04	-	-	-	-
WQ0002128	Pebble Beach Condos WWTF	NC	EATF	2	3.51	13	92.86	0	0.00	0	0.00	-	-	-	-
WQ0002314	Windward Dunes WWTF	NC	EATF	0	0.00	2	33.33	0	0.00	1	2.08	-	-	-	-
WQ0002829	KDHWWTP	NC	EATF	0	0.00	3	50.00	1	1.85	2	3.77	-	-	-	-
WQ0003044	Dunescape Villas WWTF	NC	EATF	3	5.26	10	71.43	3	5.26	1	1.75	-	-	-	-
WQ0003067	Ocean Bay Villas & Ocean Glen Condos	NC	EATF	2	3.45	45	78.95	0	0.00	0	0.00	-	-	-	-
WQ0003271	Hestron Park WWTF	NC	EATF	0	0.00	8	61.54	0	0.00	1	1.79	-	-	-	-
WQ0003437	Queens Court WWTF	NC	EATF	6	10.91	12	92.31	5	8.93	2	3.57	-	-	-	-
WQ0004059	Atlantic Station WWTF	NC	EATF	5	8.77	8	61.54	2	3.51	1	1.75	-	-	-	-
WQ0004230	A Place at the Beach III WWTP	NC	EATF	0	0.00	12	92.31	1	1.82	0	0.00	-	-	-	-
WQ0005173	Cape Royall Dolphin	NC	EATF	5	8.77	14	100.00	3	5.26	2	3.51	-	-	-	-
WQ0006254	Corolla Light No. 1	NC	EATF	1	1.85	7	50.00	1	1.92	0	0.00	-	-	-	-

RBC	Rotating Biological Contactor	4	**IT**	Imhoff Tank	1	**AS**	Activated Sludge	3
SBR	Sequencing Bach Reactor	11	**OD**	Oxidation Ditch	5	**EATF**	Extended Aeration	24

APPENDIX 2. List of treatment facilities evaluated in this study and their percent exceedences of effluent quality limits (continued).

				Total Suspended Solids		Nitrate		Biochemical Oxygen Demand		Total Coliform		Total Nitrogen (>10mg/L)		Total Nitrogen (>30mg/L)	
NonHazID/ Permit ID	**Name**	**State**	**Type**	**# Months Exceed**	**% Months Exceed**	**# Months Exceed**	**% Months Exceed**	**# Months Exceed**	**% Months Exceed**	**# Months Exceed**	**% Months Exceed**	**# Months Exceed**	**% Month s Exceed**	**# Months Exceed**	**% Months Exceed**
WQ0006863	Genesis Condos WWTF	NC	EATF	0	0.00	11	78.57	4	7.14	0	0.00	-	-	-	-
WQ0007103	Sound Of The Sea SBR WWTF	NC	EATF	3	5.36	12	60.00	0	0.00	0	0.00	-	-	-	-
WQ0007256	Baycliff	NC	EATF	2	3.70	1	33.33	2	3.64	0	0.00	-	-	-	-
WQ0009772	Monteray Shores	NC	EATF	0	0.00	9	75.00	1	1.85	2	3.70	-	-	-	-
WQ0011030	The Arboretum & Ocean Greens WWTF	NC	EATF	3	5.56	6	60.00	1	1.82	0	0.00	-	-	-	-
WQ0011313	Peppertree Resort WWTF	NC	OD	5	8.77	37	86.05	13	22.81	3	5.26	-	-	-	-
WQ0013027	Sea Isle Plantation North WWTF	NC	EATF	9	16.07	14	100.00	8	14.29	0	0.00	-	-	-	-
WQ0014550	Camp Don Lee-Arapahoe WWTP De	NC	SBR	21	50.00	no data	no data	9	20.45	10	22.73	-	-	-	-
WQ0018420	Ocean Club WWTF	NC	OD	2	3.85	1	100.00	8	15.38	2	3.85	-	-	-	-
WQ0018992	Southwinds Condos WWTF	NC	EATF	0	0.00	11	78.57	0	0.00	0	0.00	-	-	-	-
WQ0020084	The Villas Condominums	NC	EATF	0	0.00	3	50.00	2	4.17	0	0.00	-	-	-	-
46421	Hammonton WTPF	NJ	OD	no data	no data	0	0.00	no data	no data	1	1.52	0	0.00	0	0.00
47091	Winslow TWP WWTP	NJ	OD	no data	no data	no data	no data	no data	no data	0	0.00	1	1.79	0	0.00
46537	Landis WWTP	NJ	AS	0	0.00	no data	no data	0	0.00	0	0.00	0	0.00	0	0.00

RBC	Rotating Biological Contactor	4	**IT**	Imhoff Tank	1	**AS**	Activated Sludge	3
SBR	Sequencing Bach Reactor	11	**OD**	Oxidation Ditch	5	**EATF**	Extended Aeration	24

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