FLORIDA DEPARTMENT OF HEALTH

Florida Onsite Sewage Nitrogen Reduction Strategies Study

Task C

Literature Review of Nitrogen Reduction by Soils and Shallow Groundwater

Draft Report

June 2009

44237-001

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In association with

SCHOOL OF MINES 1874 COLORADO

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TASK C
DRAFT REPORT

Literature Review of Nitrogen Reduction by Soils and Shallow Groundwater

Prepared for:

Florida Department of Health
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Section 1.0 Introduction

1.1 Project Background

As a result of the widespread impacts of nitrogen on groundwater and surface waters in Florida, the management of nitrogen sources, including onsite wastewater treatment systems (OWTS), is of paramount concern for the protection of the environment. As part of Task C of the Florida Onsite Sewage Nitrogen Reduction Strategies (FOSNRS) Study, a review of available research related to the fate and transport of nitrogen is being developed. The primary objectives of this review are to:

- Assess the current available information on nitrogen treatment in soils and the effects to the receiving groundwater;
- Develop a searchable database of available literature concerning nitrogen groundwater contamination and OWTS;
- Assist in the conceptual understanding of the fate and transport processes that influence distribution of nitrogen in groundwater; and
- Guide future field evaluation efforts and provide additional information to the development of a modeling tool for simulation of nitrogen in groundwater (Task D).

The following presents a literature review to assess the current state-of-knowledge regarding the fate and transport of nitrogen and its movement and distribution in groundwater related to OWTS. The review will identify existing studies and reports that examine the influence of OWTS-derived nitrogen inputs, the transformative processes that impact nitrate distribution, and the key factors that result in a significant effect to groundwater quality from OWTSs. As part of the literature review, a database of the references was developed in conjunction with this summary report. This database (see separate Excel file “CSM_C-1 Nitrogen Soil-GW Studies”) includes a summary table of the relevant features and parameters of each modeling study. As a result of the large number of identified sources, some studies that were deemed as not valuable to this effort and are mentioned in this report, but are not described in detail and the reader is directed to the database for further information.

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1.2 Nitrogen in Ground Water; Conceptual Considerations

Nitrogen is an important concern for water quality and nitrates represent perhaps the most common groundwater pollutant. Animals, crops, ecosystems, and human health can be adversely impacted by the presence of nitrogen in water supplies. Of these concerns, nitrate impacts to human health have been a primary consideration. The consumption of nitrates has been linked to various illnesses, including cyanosis in infants and some forms of cancer. As a result, in the United States, a maximum allowable nitrate concentration of 10 mg/L as N has been established as protective of human health (Canter 1996). Other agencies around the world have also established such standards for nitrates in groundwater.

Also of concern are the environmental effects on groundwater and surface water that can result from nitrogen impacts. The degradation of groundwater quality can ultimately lead to the degradation of surface waters in watershed systems that have strong groundwater/surface water interactions. Nitrogen that enters surface water bodies via these interactions can lead to algal blooms and eutrophication. These processes lead to oxygen depletion in surface waters which can be harmful to natural aquatic life. In Florida, the protection of watersheds, in particular surface water bodies, has led to the legislation of protection of these areas (i.e., the Wekiva River Protection Act).

A survey of community service wells and private domestic wells performed by the U.S. Environmental Protection Agency (EPA) indicated that over half of these water supply wells contained detectable levels of nitrate (Canter 1996). The sources of this contamination are various, and include agricultural and domestic fertilizer applications, natural sources, wastewater treatment applications, and the use of OWTS. The last category is often of concern, as nearly 25% of the population in the U.S. and 30% of all new development utilize OWTS (Lowe et al., 2007). In Florida, nearly a third of all house-holds are serviced by OWTS and 92% of water supplies come from groundwater (Briggs et al. 2007, Lowe et al. 2007).

Due to the unique features of the geology and hydrogeology, the groundwater systems and ultimately ecological systems and human health may be adversely impacted by nitrogen contamination of groundwater. The geology in Florida is characterized by the presence of sinkholes and fractures that develop in the karst limestone prevalent in many areas (Briggs, Roeder et al. 2007). These features tend to act as preferential flowpaths that can contribute to widespread groundwater contamination and potentially can impact protected surface waters.

Nitrogen transport in the subsurface is a complex process, especially when considering the nitrogen inputs from OWTS. Meeting the objectives of the FOSNRS project therefore requires the development of a conceptual understanding that includes the relevant fate and transport processes, parameters, and simulation approaches that will appropriately achieve the goals of the project. Figure 1-1 summarizes the conceptual understanding of the inputs of nitrogen and the transformative and advective processes that lead to nitrogen contamination of groundwater. The FOSNRS project should result in tools that will consist of the adequate level of complexity to represent these processes to accurately simulate the fate and transport of nitrogen species.

Proper OWTS design, installation, operation, and management are essential to ensure protection of the water quality and the public served by that water source. Assuming soils and site conditions are judged suitable, a wide variety of OWTS are designed and implemented (U.S. EPA, 1997, 2002; Crites and Tchobanoglous, 1998; Siegrist, 2001). Conventional OWTS rely on septic tanks for the primary digestion of raw wastewater followed by discharge of septic tank effluent (STE) to the subsurface soils for eventual recharge to underlying groundwater (Crites and Tchobanoglous, 1998; Metcalf and Eddy, 1991; U.S. EPA, 2002). However, increasing uses of alternative OWTS rely on additional treatment of the STE prior to discharge to the environment in sensitive areas or may eliminate use of a septic tank altogether.

Septic tanks are anaerobic and have long solids retention times (e.g., years) that can enable digestion resulting in a reduction of sludge volume (40%), biochemical oxygen demand (60%), suspended solids (70%) and conversion of much of the organic nitrogen to ammonium (Reneau et al. 2001). Septic tanks are also important as they attenuate instantaneous peak flows from the dwelling unit or establishment. The effluent discharged from the septic tank (i.e., septic tank effluent or STE) then flows to subsequent engineered treatment or the directly to the soil treatment unit where the processes of soil adsorption, filtration, and transformation (biological and chemical) occur.

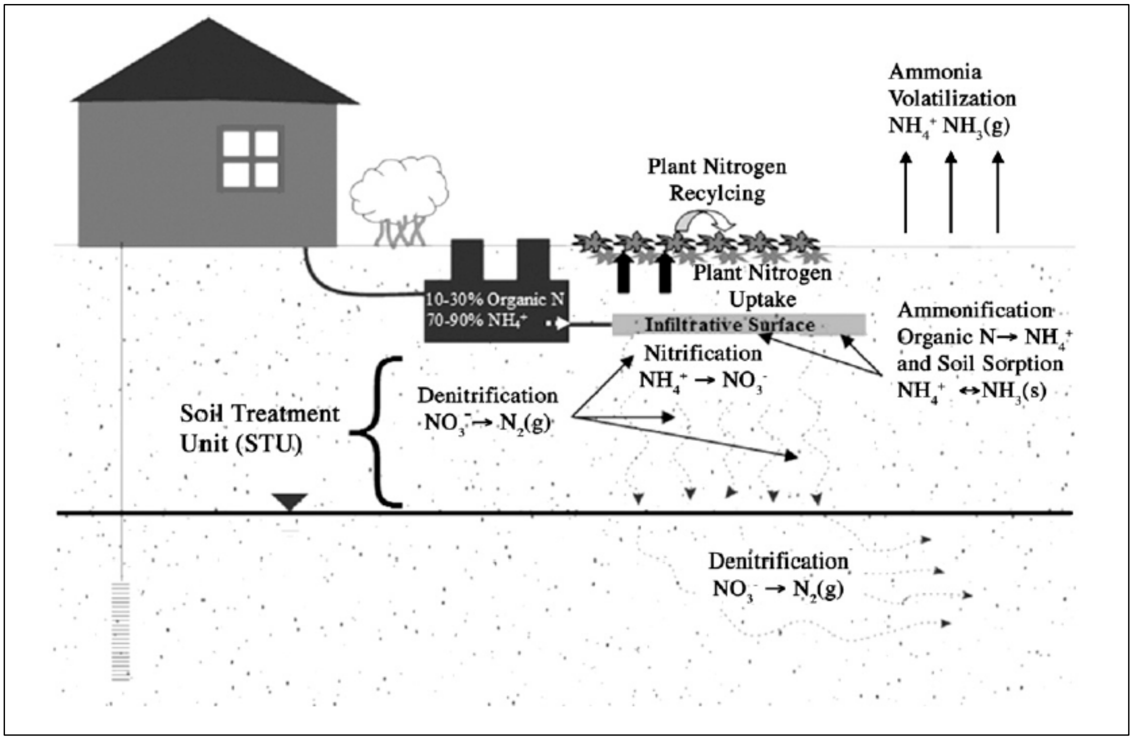

Figure 1-1: Nitrogen Processes Occurring in a Typical OWTS (Heatwole and McCray 2007)

Nitrogen waste products are a considerable component of septic tank effluent. Total nitrogen, composed primarily of organic nitrogen products and ammonium-nitrogen, is typically assumed to range between 20-190 mg-N/L in untreated waste water, and 26-125 mg-N/L in STE (Canter 1996, Crites and Tchobanoglous, 1998, Lowe et al., 2009). Furthermore, in a recent study that evaluated the composition of raw wastewater and STE, the median total nitrogen concentration in STE specific to Florida was determined to be 65 mg-N/L (average = 61 mg-N/L) (Lowe et al., 2009). In terms of mass loading to the subsurface, the median loading rate was determined to be 10 g-N/capita/d (average = 13.3 g-N/capita/d) (Lowe et al., 2009). McCray et al. (2005) suggested that an average subdivision can generate up to 2880 kg/km^2 annually. While this value is significantly higher than estimates of naturally generated deposition (600-1,200 kg/km^2 annually), it is much lower than the loading that results from fertilizer application (10,000-20,000 kg/km^2 annually). Nonetheless, OWTS should be considered a potential contributor to groundwater nitrogen concentrations.

The first stages of nitrogen transformation related to OWTS occur in the septic tank. Organic nitrogen is mineralized to the inorganic form (ammonia) via the process of ammonification, followed by volatilization to ammonium ions.

$$NH_3(aq) + H_2O \rightarrow NH_4^+ + OH^- \qquad \text{(equation 1)}$$

Once the liquid portion of the wastewater enters the drainfield through the subsurface infiltration system, nitrogen species (specifically ammonium and nitrate) are further transformed in the soil by nitrification and denitrification. Nitrification is a two step process by which ammonium is converted first to nitrite than to nitrate via biological oxidation.

$$NH_4^+ + O_2 \rightarrow NO_2^- + O_2 \rightarrow NO_3^- \qquad \text{(equation 2)}$$

Although a two step process, it can be assumed to be a one step process since the conversion of ammonium to nitrite is relatively rapid. Nitrification is either described as a zero-order or first-order reaction or via Monod kinetics. This particular reaction is of importance, as it represents the transformation from the relatively immobile nitrogen form (ammonium) to the highly mobile form (nitrate). Most studies of OWTS with suitable unsaturated soil have indicated that little ammonium reaches the underlying groundwater and that most impacts to groundwater from nitrogen are in the nitrate form. Nitrate behaves essentially as a conservative solute, with virtually no sorption or retardation processes affecting its movement in the aquifer. It is, however, subject to transformative processes.

Denitrification is the transformation of nitrate to N_2 gas.

$$5(CH_2O) + 4NO_3 + 4H^+ \rightarrow 5CO_2 + 2N_2 + 7H_2O \qquad \text{(equation 3)}$$

Denitrification occurs in oxygen-free conditions, and is therefore seen in anoxic zones in the soil and groundwater. This reaction is typically described as first-order. However, nitrogen transformations are probably best modeled using Monod kinetics, which result in zero-order rate constants for concentrations typical of nitrate-impacted groundwater. The process, while studied extensively, is not well understood or well quantified.

Understanding denitrification in the saturated zone, while receiving much less focus in the literature, is nonetheless a potentially valuable topic. Korom (1982) provides a thorough review of denitrification in the saturated zone. Although not specific to OWTS impacts, aquifer denitrification can naturally reduce nitrate concentrations, and can be potentially enhanced via the addition of *in situ* amendments such as sucrose or methanol.

This review goes on to include data and estimated denitrification rates found in both laboratory and field studies. In order to assess the contribution denitrification makes to nitrate reductions, researchers will often use the ratio of non-reactive solute (typically chloride) to nitrate along the plume flowpath. Any relative reduction in nitrate can be attributed to denitrification, since a reduction due to mixing with ambient groundwater would not change the ratio. Depending on the aquifer conditions, previous studies concerning the reduction of nitrate concentrations specifically from OWTS identify denitrification rates as relatively small, and that most reductions occur as a result of mixing with ambient groundwater (see Reneau et al. 1989). A small number of studies however indicate that denitrification may be the dominant process, perhaps characterizing aquifers with low groundwater flux (see Hantzche and Finnemore 1992).

Section 2.0
Literature Review

The following presents a summary of available research related to the treatment of nitrogen in soils and the subsequent fate and transport of nitrogen in groundwater.

2.1 OWTS Performance – Laboratory and Field Studies

A number of studies looked at performance of either experimental or conventional OWTS in terms of the treatment of nitrogen wastes from effluent. The ability of a system to adequately treat nitrogen wastes will have a significant influence into the resulting impacts to groundwater. These types of studies are valuable in that they can indicate which factors influence the transformative processes and how various loading rates, soil types, and geochemical parameters may lead to excessive nitrogen concentrations. Furthermore, these studies suggest ways of improving performance of older or failing OWTS. A large body of research has been dedicated to this topic and is important for assessing nitrogen in groundwater; however, a full discussion on this topic is beyond the scope of this review, and therefore only a few relevant studies are indicated below.

An in-depth review of the fate and transport of contaminants from on-site systems is provided by Reneau et al., (1989). This study considers multiple factors, including soil type, loading rates, effluent quality, and carbon content. In this review the author describes the important mechanisms related to OWTS performance. Firstly, he describes the importance of conditions conducive to nitrification, namely coarse-textured soils in which aerobic conditions are dominant. This is even true in fine-grained clay soils as long as unsaturated conditions are present. Denitrification in soils utilized for OWTS is expected to be minimal except in anaerobic microsites. However, soils that are influenced by fluctuating water tables in which saturated conditions can occur will see increases in denitrification rates. For groundwater, sites which are ideal for OWTS are often the most vulnerable to nitrate impacts, since they are often well drained soils with limited capacity for denitrification. In this case, often the most important mechanism for nitrate reduction is dilution by ambient groundwater.

Cogger and Carlile (1984) looked at the performance of 15 conventional and alternative OWTSs to determine their performance in soils with high water tables in North Carolina. The alternative methods included low-pressure pipe systems, soil replacement systems, and pressure-dosed mounds. At the study site, shallow groundwater wells were installed around the systems and monitored monthly for nitrogen species. The study found in general that nitrogen species concentrations were markedly influenced by seasonal variations in the water table, although some systems experienced continuous saturation. Those systems that were continually saturated had the poorest performance, as well as those with the heaviest effluent loadings. Additionally, transport of nitrogen products was facilitated by those systems located in areas with high gradients and continuous soil saturation. The low-pressure pipe systems, designed to distribute the effluent of the entire adsorption field and provide occasional dosing rest periods, performed the best in spite of any level of saturation from the water table. The mound system did not perform well, however the authors indicate the pumps feeding the system were not operating correctly and the dosing recommendations were being exceeded. The soil replacement systems showed no improved performance over the conventional systems.

Similarly, Costa (2002) conducted a series of experiments comparing the nitrogen removal capabilities of a conventional system, two proprietary nitrogen removal systems (the Waterloo Biofilter and the MicroFAST Model), and a recirculating sand filter (RSF) system. “Nitrogen losses” are described as reduction in nitrogen from the septic tank effluent to the groundwater. Measurements were conducted over an 18 month period. Results indicate that the conventional system removed 21-25%, the Waterloo 60%, the MicroFAST removed 55%, and the RSF removed 41%.

Cogger et al. (1988) examined the performance of an OWTS on a coastal barrier island. The study considered loading rate and water table as the primarily influences on OWTS performance. Two absorption fields were constructed and sampled biweekly for a period of 18 months. Three loading rates (one, four, and six cm/day) were applied in a random fashion. Loading rate was identified as significant. Additionally, periods with a high water table in the early part of the year resulted in anaerobic conditions which inhibited nitrification. Redox conditions were generally considered low. However, in drier conditions, aerobic conditions dominated and more nitrification resulted with corresponding increases in redox parameters. The authors concluded that although loading was a factor, the fluctuations in the water table were more influential in determining the rates of transformation.

Various loading rates were applied and the resulting leaching of nitrogen compounds in an OWTS were measured (Uebler 1984). Loading rates of 7.5, 11.3 and 15 L m^{-2} d^{-1} were tested. Additionally, soil amendments (cement and lime) were also part of the experiment. Transformation of ammonium to nitrate was enhanced by the soil amendments, particularly the cement amendment when water levels were higher. Interestingly, the nitrate concentrations were highest with the lowest loading rate, particularly during high water table conditions. This observation suggests that water table level influences the production of nitrate more than the loading rate.

Lowe and Seigrist (2008) describe a pilot-scale study to evaluate the effects of infiltrative surface architectures (ISA) and hydraulic loading rates (HLR) on soil treatment of septic tank effluent. A test site was established in Golden, Colorado with three different ISAs (open, stone, and synthetic) and with two different HLRs (four and eight cm/day). Monitoring was done over a two-year period to evaluate the infiltration capacity and purification performance of the different conditions. Results indicate improved infiltration using the higher HLR and using the open ISA. The higher HLR resulted in increased nitrogen mass removal (42%) compared to the lower HLR. No significant difference was reported for the different ISAs. The data suggests that improved purification can be achieved by applying higher HLRs to a portion of the soil treatment area rather than a low HLR over the entire area.

In another study, Lowe et al. (2007 and 2008) describes a large field-scale study examining the purification performance of three different treatment units: a septic tank, a septic tank with a textile filter unit (TFU) and a septic tank with a membrane bioreactor (MBR). The different units were operated over a period of 16 to 28 months, with water quality monitoring for different parameters including nitrogen. Results showed an improved performance for both the MBR and TFU over the conventional septic tank, with a 30% and 61% nitrogen removal rate for the TFU and MBR, respectively (compared to the conventional septic tank only). The use of a treatment unit such as a TFU or MBR enables the application of a higher quality effluent at a higher HLR without subsequent soil clogging, although this can be dependent on the native soil characteristics.

2.2 Vadose Zone Processes and Impacts to Groundwater

Soil treatment of nitrogen from OWTS in the vadose zone can also have a significant influence on the resulting nitrogen concentrations in the aquifer. The transformations and reactions of sorption, nitrification, and denitrification described earlier are present in this zone. Nitrogen that is present as ammonium is subject to adsorption to negatively charged soil particles, plant uptake or microbial bioaccumulation. Nitrate, on the other hand, is mobile in the vadose zone but can be subject to denitrification. It is therefore important to quantify the vadose zone processes to assess nitrogen attenuation prior to entering the saturated zone.

In another study conducted by the project team members, a summary of the available literature related to nitrogen attenuation in the soil treatment unit (STU) was done to identify the parameters that influenced transformations and reactions (McCray, et al 2008). Data from available literature was collected and tabulated for nitrogen concentration vs. depth, vadose zone characteristics, and soil type. Additional data was collected considering wastewater type, hydraulic loading rates, and source type characterization. Data analysis was performed to indicate the correlation between nitrogen attenuation and the various parameters. Initial analysis indicated no significant relationship existed between expected nitrogen concentrations and depth, soil type, or HLR. A more in-depth analysis found that the data variability was most related to HLR, suggesting that this parameter may be more influential than soil type when considering nitrogen attenuation. However, the study also indicates that different soil types will have different hydraulic properties and this can influence nitrogen attenuation.

Ammonium that is not immobilized can be converted to nitrate via nitrification. This form of nitrogen, as mentioned before, is highly mobile and can impact aquifers under OWTS. Within the vadose zone, the pathway of nitrate reduction is denitrification. In the vadose zone, denitrification is the dominant process affecting nitrate concentrations below the absorption field (Wilhelm, Schiff et al. 1998) and is therefore a key process in estimating the resultant nitrate loading to the aquifer. A body of research has been involved with understanding and quantifying denitrification in the vadose zone.

Ritter and Eastburn (1988) provide a summary of available literature related to denitrification and OWTS. Based on their review of available literature, several factors which may influence nitrogen attenuation are:

- adequate supply of a carbon source;
- infiltrative surface biozones (the biozone has been shown to improve denitrification);
- OWTS with high water tables (potentially insignificant dentrification due to lack of conditions conducive to nitrification);
- dosing (likely to improve denitrification); and
- recirculating sand filters (and other aerobic treatment units may improve denitrification).

Degen (1991) conducted a study that considered multiple factors that could potentially influence denitrification processes including effluent loading rates, effluent type, dosing rates, and temperature. This study included both experiments on soil cores in the laboratory and field sampling and measurements on sites in Virginia. The predominant soil types consisted mainly of silt loams collected in Blacksburg, Virginia. Soil cores collected for the laboratory experiments were subjected to a variety of effluent dosing rates and effluent types in order to quantify the response in a more controlled environment. The study attempted to quantify the denitrification via a number of methods, including nitrate/chloride ratios, soil chemical analyses, and microbial activity analyses. Field studies used similar analyses. Additionally, an attempt was made to model the expected denitrification in the field based on the lab results. The study made several key conclusions as follows:

- Carbon content was the limiting factor for denitrification.
- Applications every 48 hours doubled the denitrification rates compared to applications every 24 hours.
- The model was not useful for predicting denitrification in the field, likely due to the more favorable anaerobic conditions present in the field study.

Tucholke (2006) provides an analysis for relating denitrification rates in the vadose zone with soil type. The study consisted primarily of identifying studies that measured denitrification rates and described the soil characteristics of the study site with the hypothesis that predictions of denitrification could be made based on soil type. While the data did not support the hypothesis, it did show that denitrification varied significantly with soil type. However, the study concluded that denitrification is a process dependent on many variables, such as organic carbon content, soil temperature, water content, and soil pH. This conclusion was verified by statistical analysis that demonstrated that data variability was dependent on the variability in the various parameters.

One of the major research concerns with quantifying denitrification is the wide variation in measured rates in different studies. This issue makes correlation of site characteristics and denitrification difficult. Tucholke et al (2007) provides a review discussing the variability seen in the literature. This variation is attributed to variations in measurement method and wide variations observed spatially and temporally in the field. For example, rates determined in the laboratory as compared to the field varied widely, as did rates determined by isotope analysis as compared to other methods. Also, site heterogeneities in limiting factors such as water content and pH also impacted the rate determination.

Nitrogen in the vadose zone that results from OWTS is subject to various transformations and reactions which are dependent on numerous factors within the soil and from the source. Attenuation of nitrogen is accomplished via sorption, plant uptake, bioaccumulation, or conversion of nitrate to nitrogen gas (denitrification). No single dominant process or parameter can be identified; rather, an interconnected complex of factors will ultimately influence the nitrogen attenuation. Due to the complexity of the issue, more research is required in the future to relate all of the processes and variables to observed changes in nitrogen concentration from the source to the groundwater.

2.3 Land Planning and OWTS Density

While a large number of studies consider lot size or OWTS density to be important factors, two studies were identified that examined these as primary characteristics for estimating potential groundwater impacts from OWTS. Ultimately consideration of lot size or septic tank density will play a key role in land planning and developments considering OWTS as the primary method of wastewater disposal.

A method of determining lot size and density related to land development in Pennsylvania was developed by Taylor that assumes the reduction of nitrate is primarily via groundwater dilution (Taylor 2003). The author reiterates the discussion of whether or not denitrification is a significant process in groundwater, and ultimately concludes that land planning must consider dilution as the primary factor in nitrate reduction, since this approach is both conservative and simple. Also, the author indicates denitrification is a poorly understood process and should not be relied on for nitrate reductions.

Similarly, Yates concludes in her study of OWTS distribution in various watersheds in the United States that the most important factor in limiting OWTS impacts is restricting system density (Yates 1985). The author looks at nitrate impacted areas in New Mexico, Colorado, New York, Massachusetts, Delaware, and North Carolina. The study cites other research in these areas that quantifies the number of septic tanks in a particular watershed and the level of nitrate impacts. However, little quantitative analysis is provided and significant conclusions that specify lot size or density of septic tanks and how that relates to high nitrate concentrations in groundwater is given.

2.4 Groundwater Monitoring Studies and Reports

A relatively large number of studies and reports were found that considered nitrate distribution, plume delineation, and estimates of the source contribution of OWTS. Generally these are characterized by various levels of groundwater sampling, and usually some effort to make conclusions as to the nature of the nitrogen impacts based on the results of the sampling. In some cases the studies or reports are quite simple, considering only nitrate concentrations. Others are highly detailed, considering not only nitrogen species concentrations, but a variety of hydraulic and geochemical parameters. Typically the more complex studies draw more conclusions as to the transport and transformative processes at work at the various sites. However, this level of complexity does not always correspond with superior results; in some cases, the simple study addresses the objectives and can make some significant conclusions related to nitrogen impacts.

A study in Helena, Montana, examined the change in groundwater nitrate distribution as correlated with the increase in population in the area (Drake and Bauder 2005). The study indicates a potential relationship between the increase in observed nitrate concentrations and the increased use of OWTS between 1971 and 2003. The study compiled data for aquifer nitrate concentrations from 10 publicly funded investigations in the defined time period. From this data, trend analysis with statistical significance methods was applied to identify any trend between the increasing population and nitrate concentration trends. Additionally, the data was plotted geographically for spatial trend analysis. The area surrounding Helena experienced a 17% increase in population and a 68% increase in septic tank use in the decade between 1990 and 2000. The statistical analysis confirmed a correlation between nitrate concentrations and increasing population. The geographical analysis also indicated a spatial trend, showing the highest increases occurred in rural areas. This was especially the case in areas overlying bedrock aquifers and areas with high density and unpermitted OWTS.

A similar study summarized the overall impacts due to OWTS in New Mexico that also considered nitrate distribution (McQuillan 2004). In this study, data was compiled in a similar fashion the study described above. The study compared the level of nitrate impacts of aquifers with largely oxic conditions to aquifers with anoxic conditions. Also, data results from geochemical isotopic fingerprinting are provided, to identify the source of nitrate contamination. Figure 2-1 shows the results using isotopic fingerprinting. This study indicated that areas with more significant nitrate occur in aquifers with oxic conditions, whereas aquifers with anoxic conditions have lower impacts due to conditions not being favorable for the transformation of ammonium to nitrate. The results of the study also indicated that isotopic fingerprinting can be a useful tool for identifying nitrate sources, which can be useful for targeting primary nitrate sources.

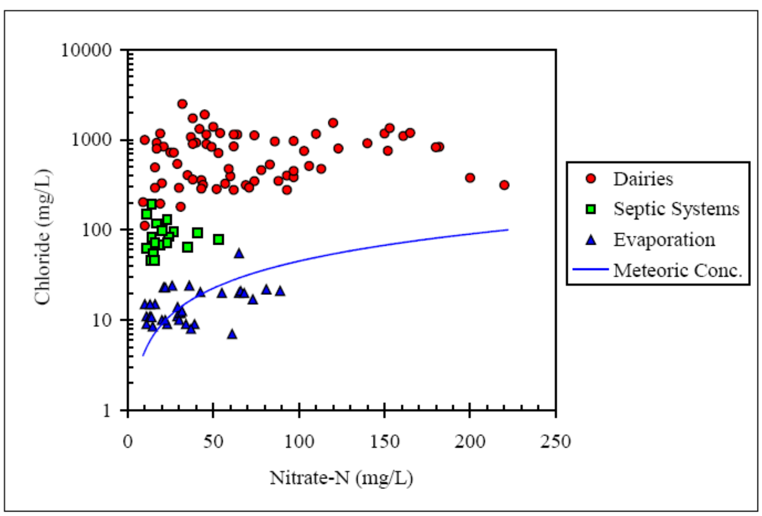

Figure 2-1: Isotopic Fingerprinting of Nitrate Sources (McQuillan 2004)

A study of the Darling Plateau region near Perth, West Australia area also examined the nitrate contributions from OWTS in a populated area served almost exclusively by individual OWTS (Gerritse, Adeney et al. 1995). It was estimated in this study that nearly 80% of the nitrogen in the subsurface could be attributed to OWTS source contributions. This study specifically looked at impacts of a neighboring surface water body approximately 70 meters downgradient. Monitoring of nitrogen species and bromide tracers showed significant decreases in inorganic nitrogen as the groundwater approached the creek. Interestingly, the surface water body had relatively high background concentrations of nitrate, but the study showed no significant contribution from this soil treatment unit.

Lapointe et al. (1990) conducted a study to relate groundwater impacts to nearby marine surface waters via tidally-influenced groundwater recharge in the Florida Keys. The area in the study is characterized by typical tropical wet and dry seasons, with most of the precipitation falling between June and October. The subsurface is a highly porous and permeable limestone that allows for rapid lateral groundwater flow. For sampling, networks of monitoring wells were established on seven residences using OWTS and one control site in a neighboring wildlife refuge. Wells were sampled monthly for approximately one year for nitrogen species and other biogeochemical factors. Groundwater flow was measured directly using an *in situ* flow meter. Surface water was also sampled. The results indicated that the contribution of nitrogen to the groundwater by OWTS was significant in this area, in some cases as much as two orders of magnitude higher than when compared to control groundwater. Ammonium was the dominant species, the result of the largely unfavorable conditions for nitrification. Surface water showed a seasonal variation, with the highest concentrations occurring in the summer months. The study also concluded that seasonal variations in tides and groundwater levels result in significant contributions from OWTS to surface waters in the Florida Keys.

A series of reports have been previously completed for assessment of OWTS contributions to nitrate contamination of groundwater and surrounding surface waters in the Wekiva watershed in Florida. This includes reports prepared by: Anderson (2006); Briggs, Roeder et al. (2007); MACTEC (2007); Otis (2007); and Young (2007). The study was initiated to protect the Wekiva river system which had been assigned protection under the Wekiva River Protection Act. The watershed occupies roughly 304,000 acres and includes parts of Lake, Orange, and Seminole counties in central Florida. The project has been performed over a number of years and includes a series of tasks in order to assess the contribution to groundwater impacts from OWTS and ultimately strategies to reduce these impacts. The tasks included:

- Field sampling for watershed characteristics, nitrogen concentrations and OWTS loading estimates.

- A literature review for refining estimates of OWTS loading.
- Integrating these estimates with estimates of other source contributions.
- Development and discussion of alternatives for reducing OTWS contributions.

Three sites were selected for sampling that met the criteria and were deemed suitable for assessment of the desired data. After completion of the tasks, a number of conclusions were reached. For example, an average home with 2.6 people on average contributes 18 pounds of nitrogen to the groundwater with the main nitrogen contributor attributed to fertilizer use. This is slightly higher than reported by Lowe et al (2008) of approximately 14 pounds of nitrogen annually (excluding outdoor residential nitrogen sources). The studies also concluded that OWTS contribution to shallow groundwater contamination was similar in terms of intensity to atmospheric deposition, however due to the areal distribution, nitrate impacts from OWTS were approximately an order of magnitude higher and distinct plumes could be delineated. Furthermore, OWTS tended to be in high-vulnerability areas and did not have effective nitrogen removal as compared to centralized wastewater methods. Figure 2-2 shows the estimated distribution when comparing the various sources.

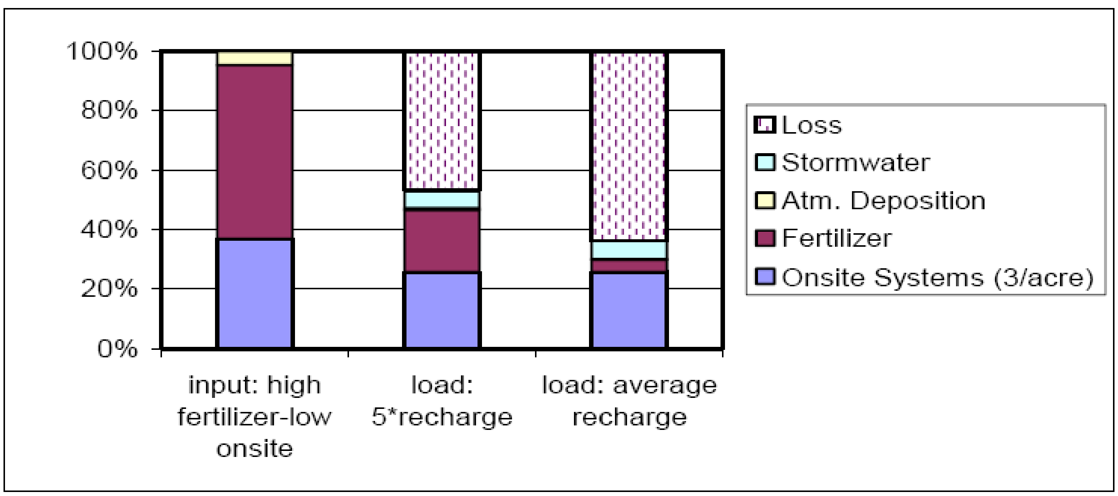

Figure 2-2: Source Contribution to Nitrate Impacts (Briggs, Roeder et al. 2007)

Other aspects of the study considered transport and transformation of nitrogen. Two factors were identified that influenced nitrogen entering the drainfield; the amount of nitrogen present in the effluent, and the level of pre-treatment prior to discharge. In the event pre-treatment was present then ammonia is converted to nitrate. However, nitrification will be limited in soils with high water tables. After discharge, if there is adequate organic carbon present, the nitrate can be denitrified to nitrogen gas.

Soils with moderate to poor drainage, fine loamy texture with clay, shallow water tables and some organic matter have the highest potential for denitrification.

Ultimately the study found that contributions from OWTS could be effectively minimized by reduced loading and improving OWTS performance with pre-treatment methods and improvement of subsurface characteristics, especially considering high water table areas.

Andreadakis (1987) performed laboratory simulations of an alternative OWTS in Greece to estimate the effectiveness of the system for nitrogen removal. The system consisted of a septic tank, gravel filter, two sand filters operated alternatively and two soil absorption trenches operated alternatively. The study found the system could achieve approximately 70% nitrogen removal. The factors that influenced the effectiveness were the compaction characteristics of the filters and soil, loading rates, and variability in saturated/unsaturated conditions.

Reneau (1977) conducted a study of changes in inorganic nitrogen compound concentrations from a septic tank in a soil with a fluctuating water table in Virginia coastal plain area. Samples were collected and analyzed for nitrate, nitrite and ammonium ions over a three year period. The relationship between nitrate and ammonium and distance is demonstrated by the ratio of these constituents to chloride (Cl^-). Assuming that chloride undergoes no significant transformations or adsorption, any variation in the ratio can be the result of either adsorption or transformation. In this case, the ratio of ammonium to chloride decreased with depth, indicating that at higher points anaerobic conditions dominated and nitrification could not take place. Following this trend, decreases in the nitrate to chloride ratio suggested that in some areas denitrification could take place due to the rising water table.

Arnade (1999) examined the relationship between nitrate well contamination and distance from OWTS as related to seasonal variations in water level in Palm Bay, Florida. The study area experiences high precipitation during the summer months and results in high water tables in sandy soils that cause septic tank overflows and ultimately groundwater contamination. Results indicated that during the wet season, nitrate concentrations tended to be higher as distance increased as compared to the dry season, although the opposite was true closer to the OWTS. The reasons provided for this observation were perhaps dilution, plant uptake or enhanced transformation. This reasoning seems suspect, as if dilution is a factor in reduced concentrations, then concentrations should follow the same pattern throughout the flow path.

Walker et al. (1973a and b) describes two studies that look at nitrogen transformations of septic tank effluent in sands. The first study focused on transformations in sand while the second study examined transformations related to groundwater quality. Research was done at the field scale at five separate locations in Wisconsin. In all cases, effluent was ponded near the surface due to the formation of a "crust" (aka, the biozone) which was the result of biological processes. As a result, unsaturated flow rates were extremely low (8 cm/day). The biozone conditions were favorable for nitrification where groundwater was not present. Most of the sites showed complete nitrification was possible at six centimeters below the biozone. One site had a high water table and as a result nitrification did not occur unless seasonal variations resulted in a lowering of the water table. Denitrification was identified in an underlying clay layer at some of the sites, although this was not the case if the site had an underlying sandy layer. In the groundwater, the dominant process reducing the nitrate concentrations were dilution with ambient groundwater and not denitrification due to the nature of the well-aerated sandy soils and the low carbon content of the groundwater. The authors concluded that in order to minimize impacts from OWTS in such aquifers, considerable land size is necessary in order to maximize the effects of dilution from clean water.

Harman et al. (1996) looked at the groundwater impacts resulting from an OWTS at a school in Langton, Ontario, Canada. In this community, over 30% of the water supply wells exceeded the standard for nitrate. Multiple sources, primarily from OWTS use and agricultural practices contributed to the high nitrate concentrations. The study aquifer in question was characterized by fine to medium sands and has a relatively high groundwater velocity (170 meters/year). The wastewater from the facility was largely from washrooms, as the site had no laundry facilities present. The effluent was primarily ammonium. At the site over 400 samples were collected at 45 multilevel monitoring points at various locations downgradient of the OWTS. Samples were collected for all major ions, DOC, alkalinity, pH, and dissolved oxygen. The results found high nitrate concentrations were observed (20-120 mg/L) and extended over 100 meters downgradient owing to the high groundwater velocity. Vadose zone residence time was one to two weeks but did not appear to allow for complete conversion of ammonium to nitrate. However, geochemical analyses indicated reduced ammonium and organic carbon concentrations coinciding with increases in nitrate which suggest that nitrification was occurring. Denitrification was limited and isolated due to low levels of organic carbon and aerobic conditions. It appeared that most of the reduction of nitrate along the plume extent was likely due to natural dilution; denitrification was limited by low levels of organic carbon and aerobic conditions.

Robertson et al. (1991) studied the OWTS impact to sand aquifer from two single-family homes in Ontario, Canada. The first site was a home in Cambridge, Ontario. The surficial aquifer was characterized as a coarse sand overlying a low permeability silt. The home was occupied by four people. The second site in Bracebridge, Ontario was situated on a fine sand aquifer with a household occupied by two people. Major ion geochemistry and typical septic tank nutrients were sampled. Bromide tracer tests were also performed. Both sites showed evidence of nitrification due to high concentrations of nitrate, and low concentrations of dissolved organic carbon and ammonium. High concentrations of nitrate were observed more than 130 meters downgradient from the sources which suggested little or no denitrification was occurring and that aquifer conditions were favorable for considerable nitrate migration. However, almost complete denitrification was observed in the carbon rich river sediments downgradient. In this aquifer, it was concluded that due to the low dispersive nature of this type of aquifer, current minimum distance to well regulations may not be protective. This was verified by natural-gradient bromide tracer tests.

Another study in the literature conducted water sampling from domestic supply wells in five unsewered subdivisions in Wisconsin (Tinker 1991). The objective of the study was to identify the sources of nitrate impacts to drinking water. Water samples were collected on two separate occasions from supply wells in five subdivisions and tested for nitrate concentrations. Sources of nitrate impacts were assessed by the location of the OWTS and the water supply well in relation to the groundwater flow direction and comparison of the results of three mass-balance models. The combination of methods resulted in a good correlation between the locations and the groundwater flow, as well as the results of the mass-balance modeling. The author concluded that elevated nitrate concentrations could be attributed to lot size (from the mass-balance modeling) and locations of water supply wells and OWTS.

Reay (2004) examined the impacts from OWTS to near shore areas along Chesapeake Bay. Due to the sandy characteristics of the aquifer and the shallow water table, significant nitrate impacts to near shore sediments were observed. Multiple characteristics were analyze at three separate sites in Virginia considered representative of the Virginia coastal plains. Among the characteristics were depth to water, aquifer thickness, soil characteristics, lot size and persons per household. Groundwater was sampled for nitrogen species and phosphorus as was neighboring surface waters. The author noted the lot size and relatively high loading rates contributed to the observed concentrations. Furthermore, the sites showed potentially high nitrification rates are likely present due to the observed concentrations of nitrate versus ammonium, and that very little denitrification was occurring, which led to significant nitrate impacts to nearby surface waters.

A sampling study to quantify the nitrogen impacts from OWTSs was performed for a community in Nevada (Rosen et al. 2006). This study combined field data and a mass-balance approach to assess the nitrogen impacts attributed to OWTS. The area under study was a densely populated area north of Reno, Nevada. In this area, 2,070 septic tanks were in use. Annual precipitation was low (20-25 cm/year) and recharge water to the aquifer also came from irrigation ditches (54%) and septic tank effluent (17%). Four separate sites were sampled monthly for one year. No geochemical or hydraulic parameters were collected. The final results of the estimates indicated that 25-30 metric tons of nitrogen in the groundwater could be the result of OWTS use, although the authors concede that considerable error is possible and that future studies considering more parameters will be needed.

2.5 OWTS Plume Geochemistry

A number of researchers went beyond the approach of considering nitrate concentrations only and considered numerous factors of OWTS-generated nitrate plumes to delineate the important parameters that may affect nitrate transport and transformation. In most cases, the study collected samples related to all major ions present in groundwater (K^+, Cl^-, NO_3^-, SO_4^{-2}, Ca^{+2}, Na^+, Mg^{+2}, PO_4^{-3}), field parameters such as pH, conductivity, alkalinity, dissolved oxygen, and other factors such as dissolved organic carbon. Additionally, complete characterization of the aquifer parameters were collected, such as those related to soil type and groundwater flow and velocity. These studies were often performed at the field scale, although some laboratory experiments were done as well. The value of these studies is the opportunity to understand how the aquifer responds to transformative processes in terms of changes to other constituents and physical characteristics, and provide a rationale for the extent of impacts observed.

Wilhelm et al. (1998) looked at changes in geochemistry for two operating OWTS in a sandy aquifer in Ontario for evidence of nitrate transformation. The objective of the study was to confirm a conceptual model that indicated the transformative processes related to nitrogen would result in the creation of redox zones. Changes in geochemical parameters could be measured to confirm the presences of these zones. Sampling was performed along the wastewater flow path at two sites from 1987 to 1990. In the septic tanks themselves a primarily anaerobic environment existed, with low concentrations of nitrate and high concentrations of ammonium and carbon. Aerobic conditions dominated below the discharge pipes. The research indicated that nitrification zones could be identified in areas with decreases in pH and alkalinity, whereas zones of denitrification were characterized by increases in both parameters. Differences in the sediment composition led to different behaviors of nitrate in the groundwater. For example, the plume at the second site entered carbon-rich sediments near a river bed, ultimately leading to complete denitrification and an increase in alkalinity.

Another study looked primarily at changes in inorganic nitrogen compounds related to septic tank effluents, but also looked at subsequent changes in pH and Eh (redox potentials) in a groundwater system in Virginia (Reneau 1979a). The objective of the study was to relate changes in concentrations as related to distance traveled, soil properties, and seasonal variation. At three different sites, rows of sampling wells were established at 1.5, five, 10, and 13.5 meters downgradient and sampled semi-monthly for phosphate, nitrogen specifies, Eh, and pH. Sampling occurred over a two-year period. For nitrate, concentrations reached a maximum (average values ranging from 2.7 to 3.9 mg/L) at the five meter sampling points then decreased with distance. This was attributed to nitrification of ammonium and the subsequent denitrification of nitrate to a relatively large degree. This was accompanied by a drop in pH and a slight increase in Eh values.

A study conducted in Ontario, Canada examined multiple geochemical factors which can be related to OWTS impacts (Ptacek 1998). Temperature, pH, dissolved organic carbon redox conditions and nitrogen species concentrations were all sampled. The original OWTS effluent contained 98 mg/L of nitrogen as ammonium. Nitrate concentrations were high in the shallow portions of the aquifer, along with diminishing concentrations of DOC downgradient. pH stayed near neutral which was attributed to the buffering capacity of the aquifer due to carbonate content. Nitrate concentrations were low, which may suggest low rates of denitrification.

Robertson and Blowes (1995) observed nitrate concentrations in an acidic OWTS plume. The study site was again located in Ontario, Canada at a location using an OWTS for wastewater at a seasonal-use cottage. Sampling was performed at 38 piezometers adjacent to and underneath the infiltration bed. Major ion geochemistry samples were collected. Subsurface soil characteristics were various, from clays to silts to sands. The water table was generally consistent (1.5 meters below the field tiles), but became much shallower during the off-season winter months. In this system, background pH was naturally low; however, more acidic conditions existed within the plume core. Ammonium levels dropped substantially suggesting nitrification was occurring. The authors suggest that changes in nitrate concentrations downgradient were due to denitrification that was facilitated by relatively high levels of dissolved organic carbon and anaerobic conditions. Furthermore, at greater depths in the groundwater, high levels of sulfate coinciding with drops in nitrate concentrations suggested an alternative pathway for consumption of nitrate via sulphur oxidation.

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Section 3.0
Discussion and Analysis

The literature review revealed important conceptual information for the assessment of nitrogen impacts in groundwater due to OWTS. One of the primary objectives of the review was to examine the current state-of-knowledge related to the primary influences on the fate and transport of nitrogen following the initial loading into the soil from the use of OWTS. A cascade of processes and factors contribute to nitrogen contamination. These include loading rate, OWTS density, soil characteristics, oxygen content, and aquifer recharge and water table elevation and fluctuation. Primary factors that can lead to significant nitrogen concentrations are found in both the septic tank and the vadose zone and an understanding of the processes within these is important rather than just considering processes in the aquifer.

The transformative processes of nitrification and denitrification require further study and quantification, especially when considering septic tank performance and processes within the vadose zone. Additionally, an understanding of the aquifer characteristics, such as groundwater velocity and flux estimates can greatly improve the quantification of dilution for reduction of nitrate. Nitrification can be inhibited by high water tables and overloading of OWTS. Likewise, denitrification, a potentially important process in the reduction of nitrate in groundwater, requires anoxic conditions in the presence of adequate carbon sources.

An improved understanding and assessment of field conditions prior to septic tank design can improve performance and result in reduced impacts from OWTS. A large number of reports have been generated that are essentially monitoring reports describing nitrogen levels in observation wells. In some cases, these reports considered factors beyond nitrogen concentrations and included multiple geochemical factors as well. These studies have immense value in the light of other studies, in which the influence of important factors for nitrogen contamination can be quantified in real field-scale studies. Specifically, these studies provide quantitative data concerning:

- Downgradient and cross gradient nitrogen concentrations in groundwater which provides plume delineation spatially and in some cases temporally;
- Site-specific subsurface characterization such as soil type and distribution;

- Groundwater measurements that provide data concerning groundwater flow paths, velocities, and fluxes which can strongly influence the extent of the impacts in terms of concentrations and distance from the OWTS;

- Total nitrogen loading rates at the source, which when compared to downgradient nitrogen concentrations provide data concerning OWTS performance, and nitrogen conversion rates; and

- In some cases, surface water sampling which may indicate the level of groundwater/surface water interaction and/or transformative processes present at the groundwater /surface water interface.

The conclusions reached using the data in these studies can then be applied for nitrogen impact estimates in future studies and how to appropriately monitor and sample a site that will utilize OWTS. Furthermore, these studies can be examples for assisting in OWTS design and installation to minimize nitrogen in groundwater. Lastly, data from these studies can be applied to the further study of the OWTS and vadose zone processes affecting nitrogen transport and fate in groundwater and lead to better predictive methods for estimating nitrogen impacts.

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Section 4.0 Conclusions

The literature review revealed numerous factors that may influence nitrogen impacts to groundwater resulting from the use of OWTS. Transport and fate processes that are present in the OWTS, vadose zone and saturated zone all will influence the extent of nitrogen impacts to groundwater. Furthermore, these factors, along with factors related to groundwater/surface water interactions will also determine if nearby surface water bodies are adversely affected. In doing site assessments, it is therefore important to develop sampling plans that can collect data for a majority of the factors described in the literature. Also, predictive efforts and efforts aimed at reduction of impacts should also consider the findings of the literature review. A brief summary of important points is as follows:

- Some studies identified lot size and location of water supply wells in relation to OWTS as important factors in determining nitrate contamination to groundwater.
- OWTS loading rate can significantly impact the performance of the soil and ultimately nitrogen concentrations in the aquifer.
- In certain cases, water table fluctuations may be a larger factor than loading rate of nitrogen on the overall OWTS performance.
- Nitrogen reduction in the vadose zone is an important determining factor for nitrate concentrations in the groundwater. This is a complex process dependent on numerous factors that need to be studied in depth.
- Nitrification can be influenced by soil type and appropriate loading of an OWTS. Sikora and Corey (1976) indicate that coarse-textured strongly-aggregated soils favor nitrification while finer textured soils lead to the development of anaerobic conditions and inhibit the process.
- Sandy soil aquifers are particularly susceptible to nitrate contamination, particularly in the case of low carbon content aquifers with relatively high groundwater velocities. In these cases, high concentrations and large areas of impact may be expected due to the lack of transformation and the distance nitrate can travel in a short time period.

- Denitrification occurs largely in anoxic soils and groundwaters with adequate carbon sources. In the soil column, denitrification may occur in systems with high or fluctuating water tables that allow the creation of anoxic conditions, providing the organic carbon content of the soil is adequate. In groundwater, dilution is often seen as the dominant mechanism for the reduction of nitrate, although some studies identify denitrification as the dominant factor. This is highly dependent on site-specific characteristics.

- Denitrification, while being a well-understood process is poorly quantified and not correlated with other site characteristics especially when considering the saturated zone. This should be a significant topic of further study.

- Some studies identified the relatively high denitrification capacity of river bed sediments, particularly if they contained high levels of organic carbon. This is especially relevant if the protection of adjacent surface water bodies is a key concern.

The literature review suggests reductions in groundwater nitrogen impacts associated with OWTS are achievable with a few steps. Nitrate is highly mobile in groundwater and the only significant methods of natural attenuation is denitrification, a process that the review indicates is not always present in natural aquifers (however, it should be noted that saturated zone denitrification can be enhanced with amendments as a potential treatment process, see Korom (1992)). Therefore, reduction of nitrate contamination may be most efficiently approached in the design and installation processes when considering OWTS as a treatment alternative. Appropriate land planning and density of OWTS in new developments is a first step. OWTS should be placed within protective distance of downgradient groundwater and surface water resources. Additionally, recognizing the importance of dilution for nitrate concentration reductions, appropriate lot size should be in the design to allow adequate dilution from recharge water. Within the design of OWTS, appropriate loading rates and an understanding of OWTS effluent can achieve lower levels of nitrogen entering the subsurface. Lastly, the review indicates the performance value of appropriate treatment units can improve effluent quality by reducing nitrogen prior to infiltration.

Additional optimization can be achieved by a thorough understanding of site characteristics and how these may influence OWTS performance and ultimately nitrogen concentrations in groundwater. Numerous studies were identified that have data related to existing systems and their performance within the framework of the characteristics of the site. Certain water table conditions, soil types, and other subsurface characteristics such as pH or temperature can have an effect on the treatment ability of OWTS by varying oxygen content and redox conditions. If detrimental conditions are seen at a site being considered for OWTS, other methods of wastewater treatment may be appropriate. This can also be true for areas identified as “high-risk,” such as areas adjacent to a protected water body. Alternatively, it may be possible to amend the site conditions or use an effluent pre-treatment method to improve OWTS performance. Future work may be needed to examine the data in such studies and make attempts to correlate hydraulic and reactive parameters to observed nitrogen impacts.

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Section 5.0 References

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