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Quantification of Shallow Groundwater Nutrient Dynamics in Septic Areas

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Abstract Of all groundwater pollution sources, septic systems are the second largest source of groundwater nitrate contamination in USA. This study investigated shallow groundwater (SGW) nutrient dynamics in septic areas at the northern part of the Lower St. Johns River Basin, Florida, USA. Thirty-five SGW-monitoring wells, located at nine different urban areas served by septic systems, were used to collect the SGW samples seasonally and/or biweekly for a duration of 3 years from 2003 to 2006. Analytical results showed that there were 16 wells with nitrate concentrations exceeding the US Environmental Protection Agency's drinking water limit (10 mg L^{-1}). There also were 11 and 14 wells with total Kjeldahl nitrogen (TKN) and total phosphorus (TP) concentrations, respectively, exceeding the ambient water quality criteria (0.9 mg L^{-1} for TKN and 0.04 mg L^{-1} for TP) recommended for rivers and streams in nutrient Ecoregion XII (Southeast USA). In general, site variations are much greater than seasonal variations in SGW nutrient concentrations. A negative correlation existed between nitrate/nitrite–nitrogen (NO_x–N) and TKN as well as between NO_x–N and ammonium (NH_4^+), whereas a positive correlation occurred between TKN and NH_4^+. Furthermore, a positive correlation was found between reduction and oxidation (redox) potential and water level, while no correlation was observed between potassium concentration and redox potential. This study demonstrates a need to investigate the potential adverse impacts of SGW nutrients from the septic areas upon the deeper groundwater quality due to the nutrient penetration and upon the surface water quality due to the nutrient discharge.

Keywords Nutrient · Septic tank · Shallow groundwater

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1 Introduction

Onsite wastewater treatment septic systems are used worldwide in many rural and urban fringe areas. These systems are often developed as clusters, with a number of homes adjacent to one another, all on separate onsite sewage disposal systems. The septic tank may be used alone or in combination with other processes to treat raw wastewater before it discharges into a subsurface infiltration system. The tank provides the primary treatment by creating quiescent conditions inside a covered, watertight rectangular, oval, or cylindrical vessel, which is typically buried (U.S. EPA 2002). Conventional septic systems are designed for the removal of solids in the septic tank and the dispersal of wastewater in the associated leach field. The passage of effluent through leach field soil results in the removal of pathogens and biodegradable organic carbon at rates generally exceeding 90% (U.S. EPA 2002). Removal rates for N and P in the leach field of conventional septic systems are more modest, ranging from 85 to 95% for P and from 10 to 40% for N (Kaplan 1987; U.S. EPA 2002).

Disposal of domestic wastewater into septic systems is a common practice that introduces contaminants such as nitrate and phosphate (PO_4^{3-}) into the shallow groundwater (SGW) aquifer. Nitrate produced in the septic systems usually cannot be transformed efficiently to nitrogen gases through the heterotrophic denitrification process because of the lack of external organic carbon, leaving it to leach through the soil into the groundwater. For this reason, of all groundwater pollution sources, septic tank systems discharge the greatest total volume of wastewater directly into soils, overlaying the groundwater, and are the second largest source of groundwater nitrate contamination in USA (Canter and Knox 1985).

It has been reported that groundwater discharge provides a significant amount of nutrients and contaminants into some coastal zones (Valiela and Teal 1979; Capone and Bautista 1985; Lapointe and O'Connell 1989; Capone and Slater 1990; Lapointe et al. 1990; Maruyama et al. 2011). In areas with a shallow freshwater system, groundwater may easily be contaminated from onsite sewage treatment systems which are typically installed less than 1 m above the water table and may be flooded during heavy rains. The discharge of non-point source pollution from these systems to SGW and ultimately to surface waters could be an important source of contamination for river and estuary environments.

Approximately 23% of households in USA rely on onsite wastewater treatment systems for disposal of domestic sewage (U.S. Census Bureau 2003). More than half of these systems are over 30 years old, installed when septic system rules were nonexistent, substandard, or poorly enforced. About 33% of new construction also relies on septic systems for wastewater disposal. Managing septic systems requires correct site selection, proper installation, regular maintenance, and the detection and correction of existing failing systems. When septic systems do not function correctly, they present a serious threat to public health, drinking water, aquatic life, and wildlife. Failing septic systems are among the known contributors of pathogens and nutrients to surface and ground water. It is estimated that between 1 and 5% of septic systems fail each year (DeWalle 1981). Currently, no general census information is available regarding the number of septic tank systems used in Florida. Arnade (1999) reported that about 40,000 residents in Palm Bay, Florida, rely on septic tanks as a means of sewage disposal and on wells as a drinking water source. The high level of precipitation (>63 cm) during the months of July to September and the presence of porous sandy soils result in high water tables and septic tank overflows. Sixty residential wells in Palm Bay were tested for fecal coliform, nitrate, and phosphate to determine if the seasonality has a significant effect on the correlation between these parameters and the proximity of wells to septic tanks. This author found that groundwater samples collected at all distances from septic tanks during the wet season (July to September) contained twice as many fecal coliforms and higher concentrations of nitrates compared to samples collected during the dry season (October to June).

Recently, Wicklein (2004) evaluated the water quality of two St. Johns River tributaries, namely the Fishing Creek and South Big Fishweir Creek, receiving septic tank effluent in Duval County, Florida. Surface water samples were collected at four sites, two sites in the Fishing Creek and the other two in the South Big Fishweir Creek, during 2000 to 2002. This author found that the concentrations of nutrients ranged from 0.33 to 2.86 mg/L for total nitrogen (TN) and from <0.02 to 0.64 mg/L for total phosphorus (TP) in the surface water. The TN and TP concentrations exceeded the US Environmental Protection Agency's (US EPA) criteria for rivers and streams, 49 and 96% of the time, respectively, in nutrient Ecoregion XII. The fecal coliform bacteria concentrations were also measured on a monthly basis. Of the 115 samples, 63% exceeded the Florida State fecal coliform bacteria standard for the class III surface waters of 800 colonies per 100 ml of water on any 1 day. This author further concluded that the surface water quality was influenced by groundwater and septic tanks.

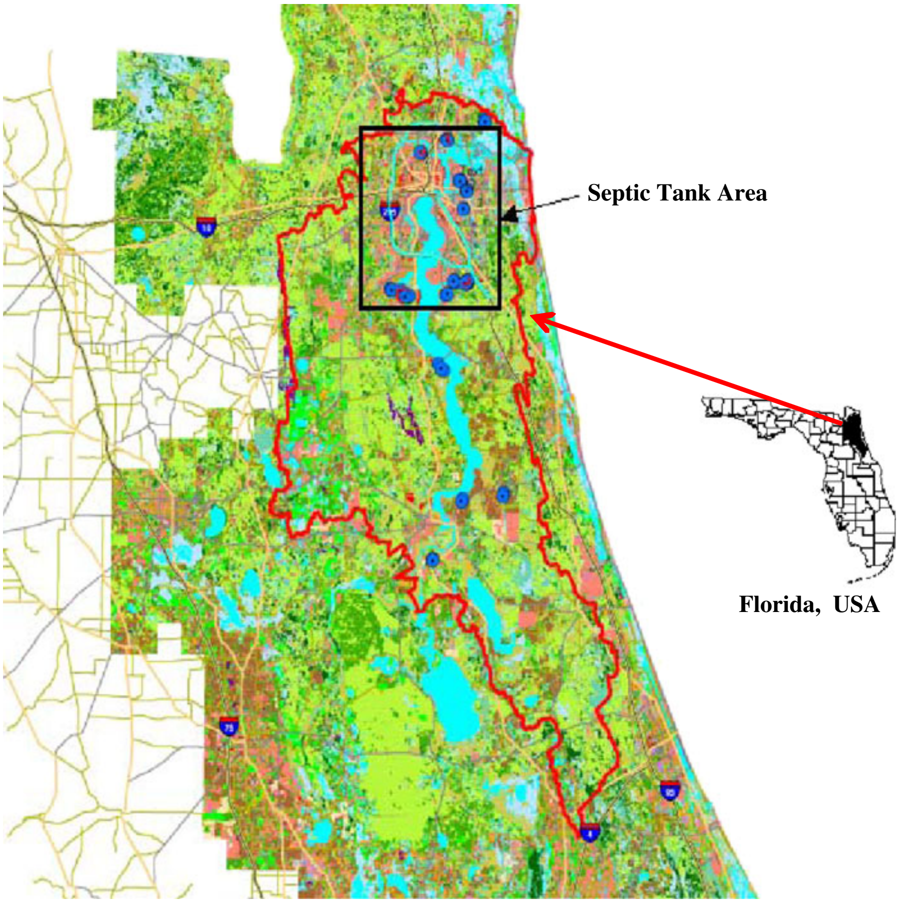
Despite a need to understand the groundwater quality status in the Lower St. Johns River Basin (LSJRB) and its potential adverse environmental impacts upon the surface water quality, there are insufficient studies that have comprehensively summarized the SGW quality status in this basin. The goal of this study was to characterize the SGW nutrient dynamics in the major septic tank service areas in the northern part of the LSJRB, Florida. The specific objectives were to: (1) evaluate the SGW nutrient contamination in the septic tank service areas using the US EPA's water quality criteria, (2) determine the site variations of SGW nutrients, (3) determine the seasonal variations of SGW nutrients, and (4) identify the relationships of nutrients to water levels and reduction and oxidation (redox) potentials in the SGW system.

2 Materials and Methods

The LSJRB is located in northeast Florida, between 29° and 30°N and between 81.13° and 82.13°W (Fig. 1). It is an area of about 7,192 km^2 and represents about 22% of the area within the St. Johns River Water Management District (SJRWMD). Land uses within the basin largely consist of residential, commercial, industrial, mining, ranching, row crop, forest, and surface water. A number of water quality problems, including point and nonpoint source pollutants such as nutrients, hydrocarbons, pesticides, and heavy metals (Durell et al. 2001), have been identified and addressed since the 1950s. In early 2000s, concerns arise regarding many failed septic tanks in the residential areas with potential leakages of excess nutrients into shallow groundwater, which leads to the development of this project.

Samples collected from 35 SGW wells, which were installed by the SJRWMD and its contractor (LBG, Inc. 2004) in the residential areas with septic tank disposal systems, were used in this study (Fig. 1). These residential areas include the following nine sites: Arlington Manner (AM), Doctors Lake (DL), Hood Landing (HL), Jacksonville Electric Authority (JEA) Julington Creek (JC), Julington Forest Subdivision (JF), Manor Del Rio Subdivision (MDL), Oakwood Villas (OV), Riverview Neighborhood (RV), and Siesta Del Rio Subdivision (SDR). The well-casing depths ranged from 4 to 7 m, which are considered as the SGW wells in Florida. The groundwater

Fig. 1 Location of the Lower St. Johns River Basin showing the septic tank service areas used in this study. The *blue symbols* are shallow groundwater wells



samples and data used for this study were collected seasonally and/or biweekly for a 3-year period by contractors during 2003 to 2006, and chemical analyses for nutrient contents were performed by the SJRWMD. Sampling activities include the collection of groundwater samples, the in-situ measurement of water level, and the slug test of hydraulic conductivity from the monitoring wells (MWs). All sampling activities were conducted in accordance with the SJRWMD's Standard Operating Procedures for the collection and analysis of water quality samples and field data (SJRWMD 2010). These standard operating procedures are in compliance with the US EPA's standard methods for groundwater sampling and analysis. Statistical analysis was performed with SAS 9.0, and all of the experimental data were statistically evaluated using F test at $\alpha=0.05$.

3 Results and Discussion

3.1 SGW Nutrient Status

The SGW nutrient dynamics in the septic tank service areas within the northern LSJRB can be characterized by nutrient constituents and other related parameters. The nutrient constituents selected for this study include total Kjeldahl nitrogen (TKN), ammonium (NH_4^+), nitrate/nitrite–nitrogen (NO_x–N), TP, phosphate, and potassium (K). Other relevant parameters, such as groundwater levels and redox potentials, were also selected in this study.

Analytical results show that the concentrations of nutrient constituents and the values of other related parameters varied from location to location as well as from season to season. Table 1 summarizes the descriptive statistics, including the number of samples; the minimum, maximum, and mean concentrations/values; and the standard deviations, of the selected nutrients and other parameters. The US EPA's water quality criteria are also given in the table. Comparison of the concentrations of groundwater quality constituents with the US EPA's water quality criteria shows that there were 132 groundwater samples with NO_x–N concentrations exceeding the US EPA's drinking water standard limit (10 mg L^{-1}), while there were 92 and 175 groundwater samples with TKN and TP, respectively, exceeding the ambient water quality criteria recommended for rivers and streams in nutrient Ecoregion XII (Table 1). Groundwater with these high TP and TKN concentrations discharged into the Lower St. Johns River (LSJR) would degrade the ambient water quality.

Further analysis of the groundwater nutrient data shows that there were 16 wells with NO_x–N concentrations exceeding the EPA's drinking water limits. However, it should be pointed out that the groundwater NO_x–N data were collected from SGW wells 7 m or less in depth. Most Florida residents who use wells as a drinking water source normally have well depths that exceed 33 m. Our study also revealed that there were 11 and 14 wells with TN and TP concentrations, respectively, exceeding the ambient water quality criteria recommended for rivers and streams in nutrient Ecoregion XII (Table 1). Results suggest that these

Table 1 Statistical shallow groundwater nutrients data in the septic tank service areas within the northern LSJRB

Parameter	Minimum	Maximum	Average	Number of samples	Standard deviation	Water quality criteria	Number of Samples exceeding criteria
TKN (mg/L)	0.00	34.93	1.44	681	5.53	0.90[a]	92
NH_4^+ (mg/L)	0.00	35.18	1.19	681	5.59		
NO_x-N (mg/L)	0.00	43.70	5.67	681	6.21	10.00[b]	132
PO_4^{3-} (mg/L)	0.00	4.03	0.23	681	0.71		
TP (mg/L)	0.00	3.99	0.24	681	0.73	0.04[c]	175
K (mg/L)	0.22	16.76	3.52	681	2.46	12[d]	5

[a] EPA's drinking water standard limits (http://www.epa.gov/safewater/mcl.html)

[b] EPA's national secondary drinking water regulations (http://www.epa.gov/safewater/mcl.html)

[c] EPA's ambient water quality criteria recommendations for river and streams in nutrient Ecoregion XII (EPA 822-B-00-021, December 2000)

[d] Europe's drinking water standard limits (Griffioen 2001)

septic tank service areas could be one of the potential TKN and TP sources for LSJR eutrophication due to the groundwater discharge.

3.2 Site Variation of Nutrients

Figures 2 and 3 show the averaged concentrations of groundwater nutrients, namely the dissolved TKN, NH_4^+, NO_x–N, TP, PO_4^{3-}, and K, from the septic tank service areas at nine sites in the northern LSJRB. In general, the concentrations of SGW nutrients varied with species and changed from site to site. For example, the averaged concentrations of dissolved NO_x–N (Fig. 2c) were 0.1 mg/L in the JEA Julington Creek, 5.5 mg/L in the Arlington Manner, and 9.5 mg/L in the Julington Forest Subdivision. Similar site variations were also observed for other nutrient species. Although the exact reasons for such site variations remain unknown, a possible explanation would be the variation of groundwater hydrology, soil properties, and the amount of septic tank leakages.

It is also apparent from Fig. 2 that the averaged concentrations of TKN and NH_4^+ were much higher in the HL and JC areas than in the rest of the areas. For instance, the averaged concentrations of TKN and NH_4^+ were above 7.4 mg/L in the HL and JC areas but were below 0.67 mg/L in the rest of the areas. The

Fig. 2 Site variations of shallow groundwater nitrogen in septic tank service areas. MW denotes the monitoring well

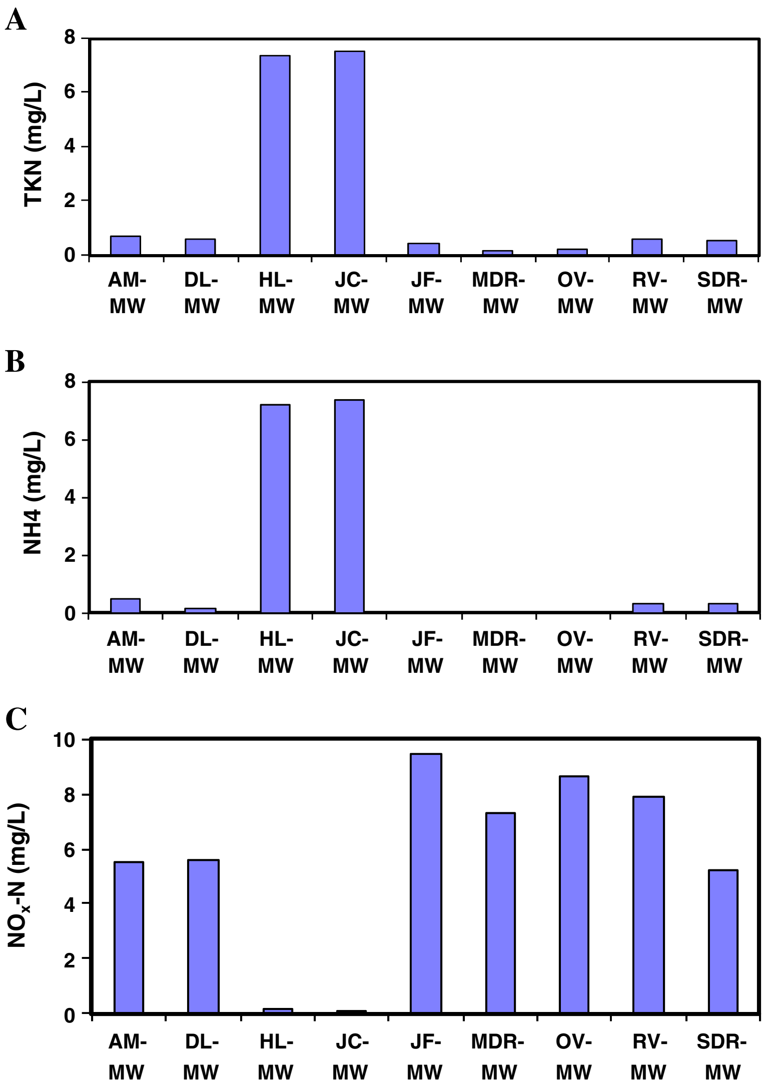
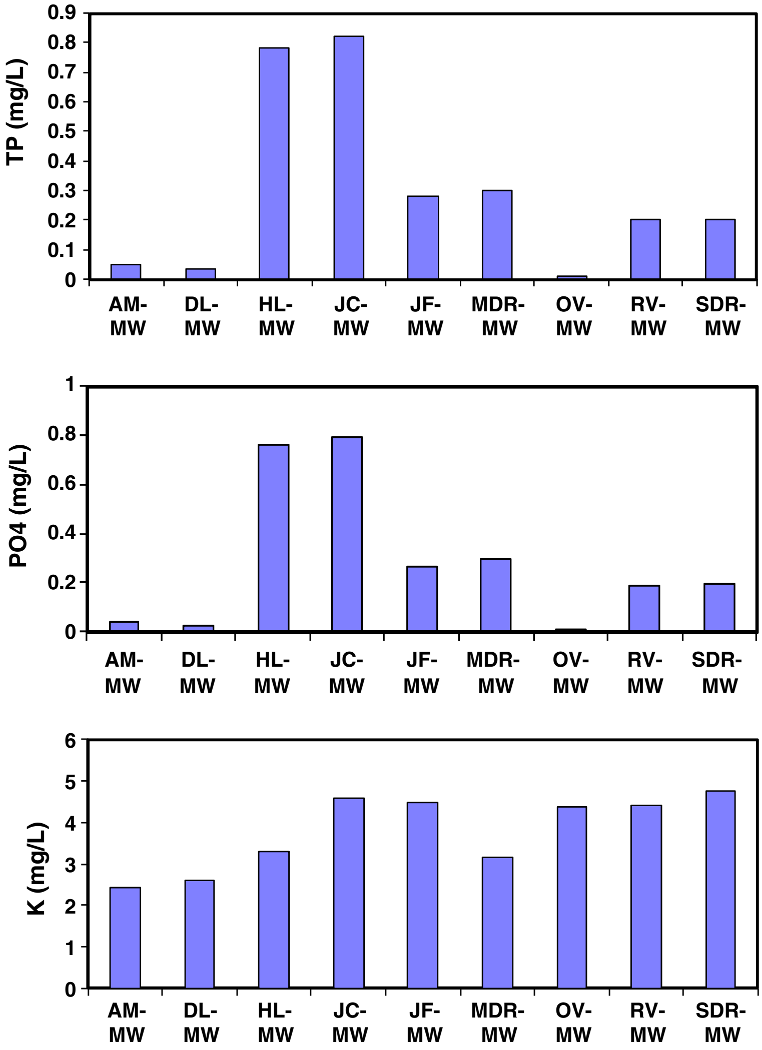


Fig. 3 Site variations of shallow groundwater phosphorous and potassium in septic tank service areas



former was more than ten-fold higher than the latter. The opposite results were observed for the concentrations of NO_x–N, i.e., the averaged concentrations of NO_x–N were lower in the HL and JC areas than in the rest of the areas. The averaged concentrations of NO_x–N were below 0.19 mg/L in the HL and JC areas but were above 5.25 mg/L in the rest of the areas. The former was more than 27-fold lower than the latter. Results suggested that an increase in groundwater NO_x–N concentration seems to accompany a decrease in groundwater TKN and NH_4^+concentrations. This finding was further confirmed with a linear regression analysis (Fig. 4). As shown in Fig. 4, the negative correlations existed between NO_x–N and TKN (R^2= 0.84) as well as between NO_x–N and NH_4^+ (R^2=0.84), although a positive correlation was observed between TKN and NH_4^+. NO_x–N is produced naturally in soil and groundwater through the microbial processes of nitrification which is the biological oxidation of ammonium to NO_x–N under aerobic soil conditions. As a result, an increase in the concentrations of NO_x–N will correspond to a decrease in the concentrations of TKN and NH_4^+.

Analogous to the cases of TKN and NH_4^+, the averaged concentrations of TP and PO_4^{3-} were much higher in the HL and JC areas than in the rest of the areas (Fig. 3), i.e., the averaged concentrations of TP and PO_4^{3-}were 0.78 and 0.75 mg/L, respectively, in the HL and JC areas but were below 0.29 and 0.30 mg/L, respectively, in the rest of the areas. The correlations among TP, PO_4^{3-}, and NO_x–N were given in Fig. 5. Good negative correlations existed between NO_x–N and

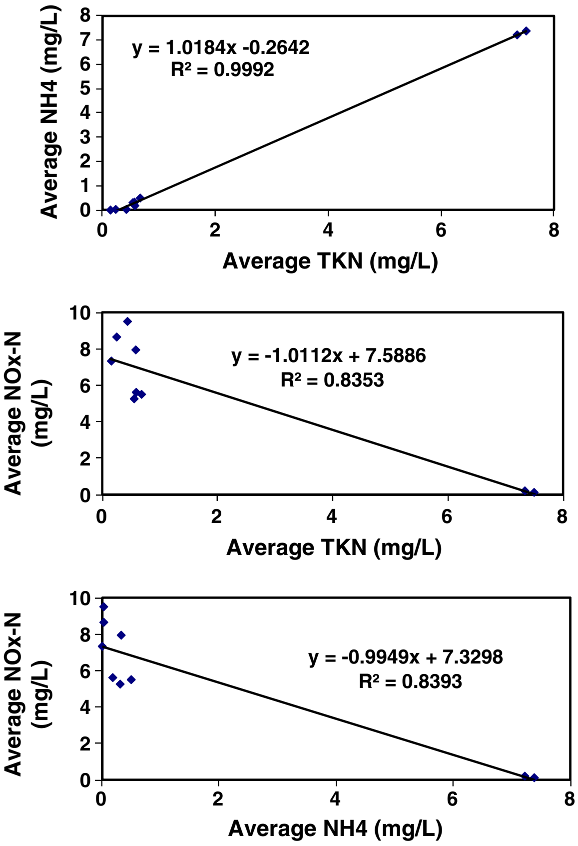


Fig. 4 Correlations of shallow groundwater nitrogen species

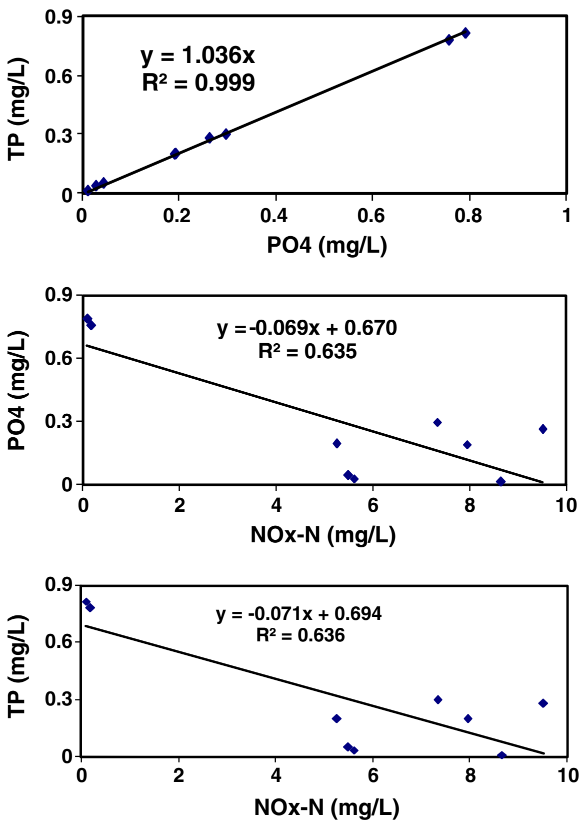


Fig. 5 Correlations of shallow groundwater nitrogen and phosphorous species

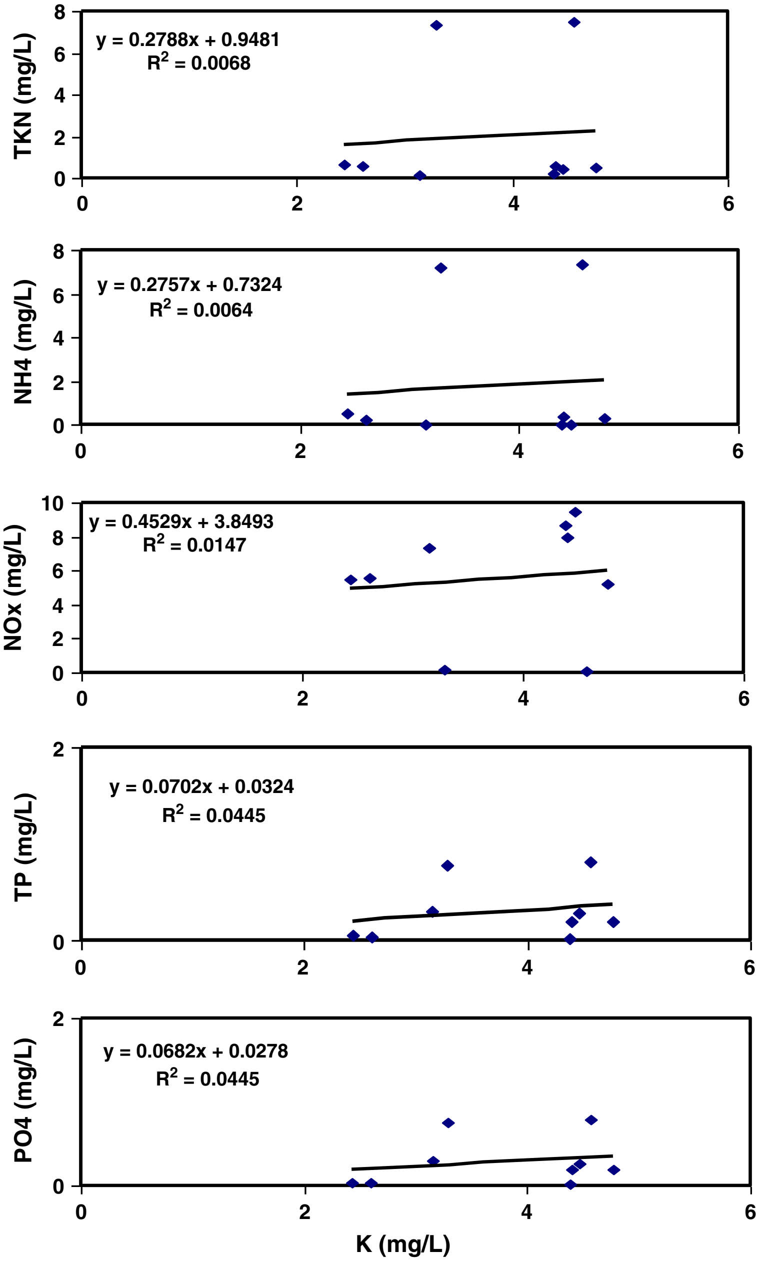
TP (R^2=0.6364) as well as between NO_x–N and PO_4^{3-}(R^2=0.6359), whereas a very good linear correlation existed between TP and PO_4^{3-}(R^2=0.9997). Results further indicate that those high concentrations of TKN, NH_4^+, TP, and PO_4^{3-}were associated with the low concentrations of NO_x–N in the HL and JC areas, while the opposite was true for the rest of the areas, i.e., the high concentrations of NO_x–N were accompanied by the low concentrations of TKN, NH_4^+, TP, and $PO_4^{3-}$for the rest of the areas.

In addition to groundwater N and P contamination, K could deserve some attention. Potassium is an important nutrient that is strongly adsorbed by clay particles in the soil. Apart from the weathering of silicate rocks, potassium can be introduced into the groundwater by the mineralization of dead vegetable material, fertilizers, and sewerage disposals. The fate of K in the soil is controlled mainly by cation exchange, and the leaching of K occurs primarily in the sand soils (Griffioen 2001). Very little effort has been devoted to investigating the site variations of K in the SGW of the LSJRB. Similar to other nutrients, the concentrations of K also changed from site to site (Fig. 3), although such variations were somewhat less profound than those of the other nutrients. Our data also showed that no linear correlations existed between K and other nutrients (Fig. 6), indicating that the major sources of groundwater K may come from different pathways and biotic and abiotic mechanisms. Further investigations also reveal that there was one site (i.e., JC) with five samples that had groundwater K concentrations greater than 12 mg/L which is a drinking water limit, reported in the Netherlands (Griffioen 2001).

3.3 Seasonal Variations of Nutrients

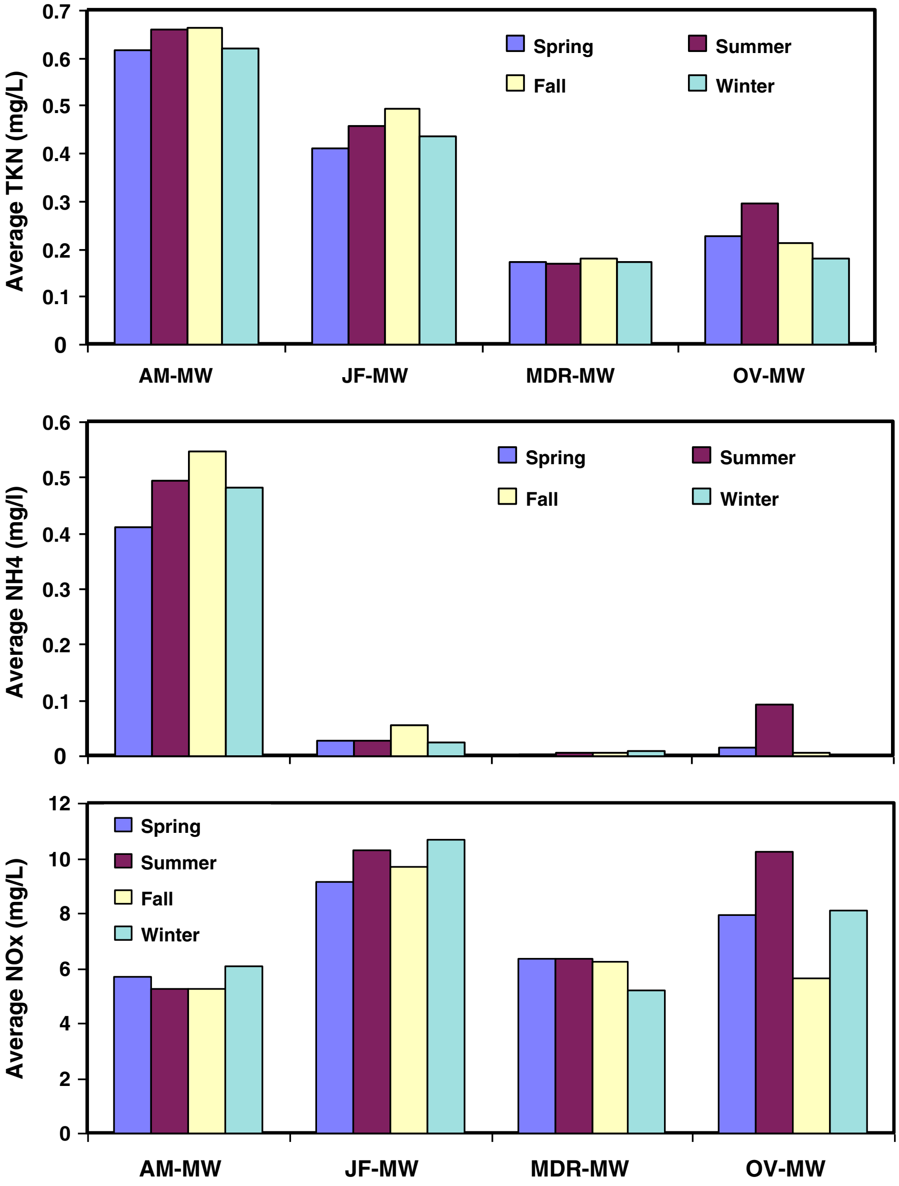
Seasonal variations of groundwater nutrients presented as the average concentrations from various monitoring sites are shown in Figs. 7 and 8. In general, the seasonal variations of groundwater nutrients in

Fig. 6 Correlations of shallow groundwater nitrogen or phosphorous species with potassium



each monitoring site were statistically significant (p= 0.05) for most of the nutrient species. A large seasonal variation in NO_x–N was observed at the OV-MW site (Fig. 7). The highest NO_x–N content was found in summer, while the lowest one was observed in fall at this site, and the difference between the two extremes was 4.59 mg/L. In contrast, the highest NO_x–N content was found in winter, whereas the lowest one was observed in spring at the JF-MW site, and the difference between the two extremes was 1.56 mg/L. Results imply that the variations in SGW NO_x–N content at each site were not consistent with the seasonality. This also is true for the other nutrient species like N, P, and K as shown in Figs. 7 and 8. In other words, a nutrient species which had a high concentration in one site may have a low concentration at another site during the same season. This occurred because of the site variations in hydraulic conditions, sources of nutrients, and biogeochemical conditions.

Fig. 7 Seasonal variations of shallow groundwater nitrogen species



3.4 Relationships of Redox Potential, Water Levels, and Nutrients

Changes in mean redox potentials and water levels among sites are given in Fig. 9. By water level, we refer to the depth of the SGW table measured from the top of the well casing near the soil surface. Reduction and oxidation reactions play an important role in groundwater geochemical processes. Redox reactions are defined as reactions in which electrons are transferred. The species receiving electrons is reduced, whereas the one donating electrons is oxidized. Redox reactions determine the mobility of inorganic compounds as well as the biologically important materials such as nitrogen and sulfur. They also govern the biological degradation of complex hydrocarbon contaminants. Redox potential is an intensity parameter of the overall redox reaction potential in the system but not the capacity of the system for specific oxidation or reduction reactions. Redox potential describes the electrical state of a matrix. In the soil and groundwater systems, redox potential controls the persistence of many organic and inorganic compounds.

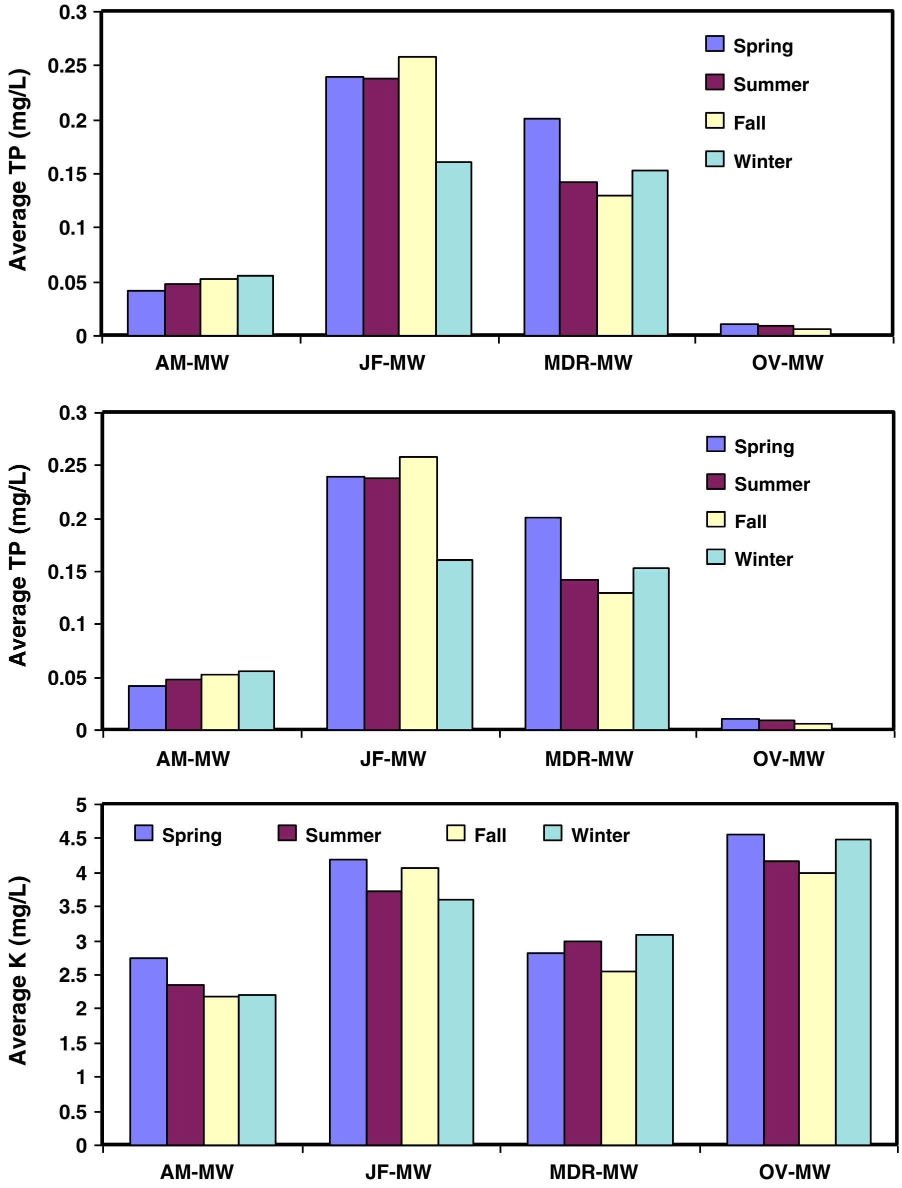
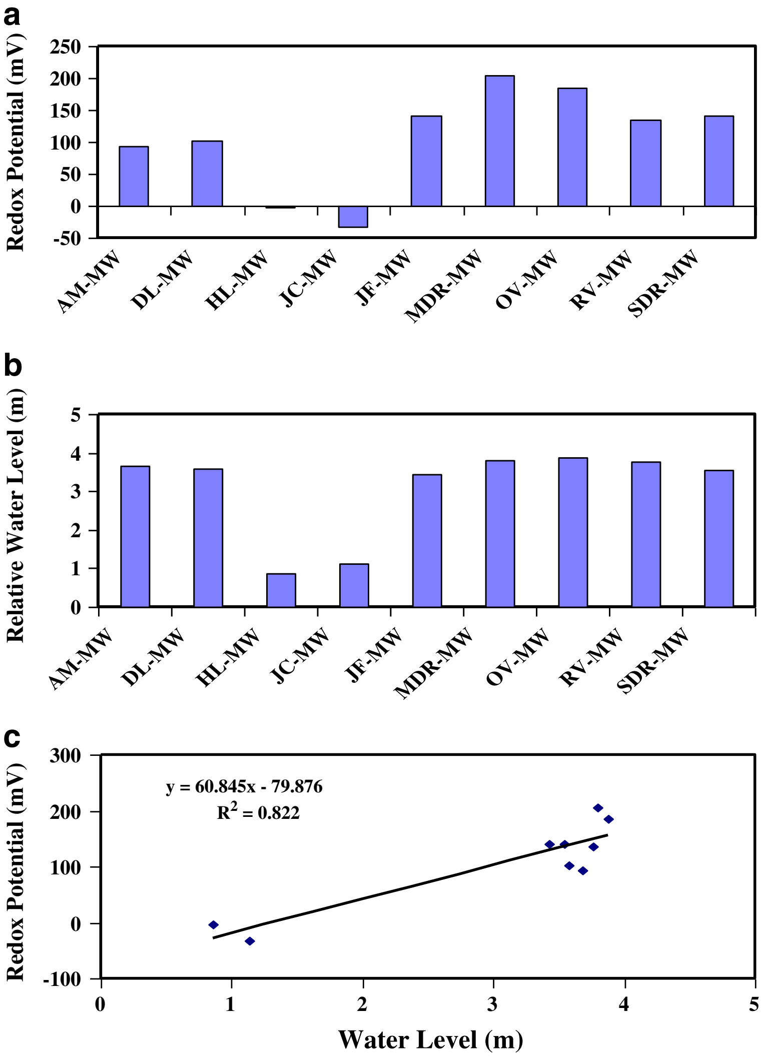


Fig. 8 Seasonal variations of shallow groundwater phosphorous and potassium

Figure 9 shows the discernable site variations in mean redox potentials and mean water levels. For example, the lowest mean redox potential (−33 mV) was observed at the JC-MW site, whereas the highest mean redox potential (205 mV) was found at the MDR-MW site. A similar result was also obtained for mean water levels, i.e., a lower (or shallower) mean water level (1.13 m) was observed at the JC-MW site, while a higher water level (3.79 m) was found at the MDR-MW. A further comparison of the relationship between the mean redox potential and the mean water level was given in Fig. 9c. It is apparent that a positive correlation (R^2=0.822) existed between redox potential and water level. A lower (or shallower) water level reduced the concentration of oxygen (which is the most important electrical acceptor) in the SGW system and thereby reduced the redox potential.

Comparisons of average nutrient concentrations with average redox potentials (Figs. 10 and 11) showed that TKN, NH_4^+, PO_4^{3-}, and TP had negative correlations with redox potentials, whereas NO_x–N had a positive correlation with redox potential. On

Fig. 9 Site variations of groundwater level and redox potential as well as correlation of groundwater level and redox potential



the contrary, there was no correlation between K and redox potential. As the redox potential increased, more dissolved oxygen was available in the groundwater and surrounding soil for the oxidation of total organic nitrogen (TON) and NH_4^+ (noted that TKN = NH_4^+ + TON) into the reduced forms of nitrogen such as NO_2 and NO_3. As a result, the concentrations of TKN and NH_4^+ decreased as the redox potential increased. The sorption behavior of P is redox-sensitive, and the bound P may be remobilized in periods with low redox potential (Braskerud et al. 2003). Therefore, an increase in redox potential would immobilize P in soils. The fate of K in the soil and groundwater is controlled mainly by cation exchange and not the redox potential. Therefore, no correlation existed between redox and K in the groundwater.

4 Summary and Conclusions

This study investigates shallow groundwater nutrient dynamics in areas served by septic systems in the northern part of the Lower St. Johns River Basin, Florida, USA. The groundwater characteristics selected in this study include total nitrogen, ammonium, nitrate/nitrite–nitrogen, total phosphorus, phosphate, and potassium concentrations and other relevant properties such as groundwater level and redox potential. Thirty-five shallow groundwater monitoring wells, located at nine different urban areas served by septic systems, were used to collect groundwater samples. The groundwater data used for this study were collected seasonally and/or biweekly for a 3-year period during 2003 to 2006.

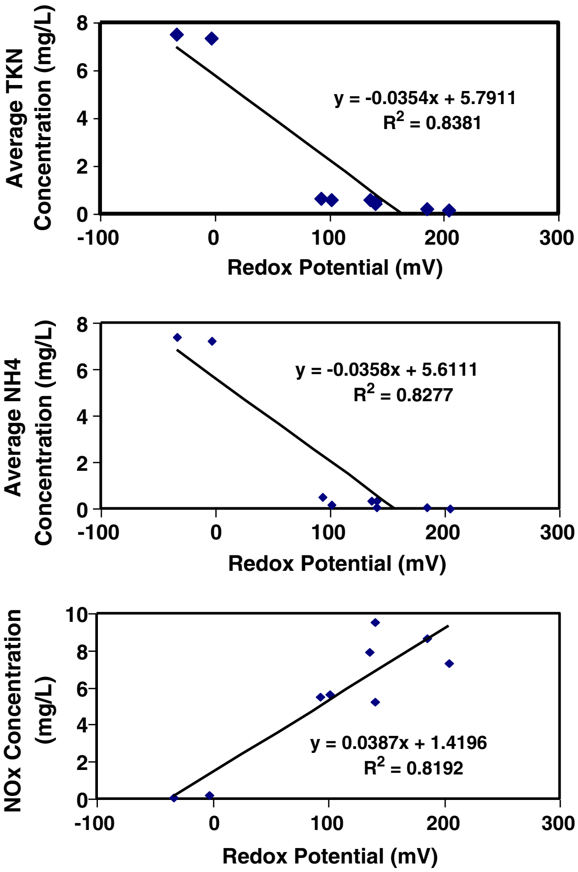


Fig. 10 Correlations of shallow groundwater nitrogen species with redox potential

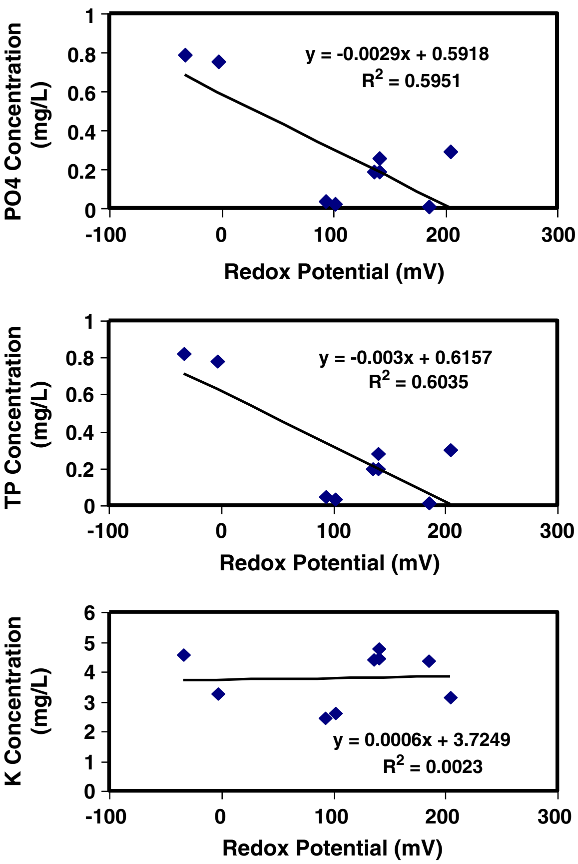


Fig. 11 Correlations of shallow groundwater phosphorous and potassium species with redox potential

Analytical results showed that about 132 groundwater samples had NO_x–N concentrations exceeding the US EPA's drinking water standard limit (10 mg/L), whereas there were 92 and 175 groundwater samples with TKN and TP, respectively, exceeding the ambient water quality criteria recommended for rivers and streams in nutrient Ecoregion XII (southeastern area). Furthermore, there were 16 wells with NO_x–N concentrations exceeding the US EPA's drinking water limits, and 11 and 14 wells with TN and TP concentrations, respectively, exceeding the ambient water quality criteria recommended for rivers and streams in nutrient Ecoregion XII, which could contaminate the LSJR due to the groundwater discharge. Very little effort has been devoted to investigating the groundwater K contamination in Florida. Our study discloses that there was one site with five samples having groundwater K concentrations greater than 12 mg/L which is a drinking water limit, reported in Europe. It should be emphasized that the nutrient samples were collected from the shallow groundwater system with a depth of less than 7 m. Most Florida residents, who use wells as drinking water source, have the wells with a depth of greater than 33 m.

In general, seasonal variations of shallow groundwater nutrients in each monitoring site are statistically significant (p=0.05) for most of the nutrient species. However, variations in shallow groundwater nutrients at each site were not consistent with the seasonality. In other words, a nutrient species with a high concentration at one site may have a low concentration at another site even during the same season. This occurred because of the site variations in hydraulic conditions, sources of nutrients, and biogeochemical conditions. It is also apparent that the site variations are much greater than the seasonal variations in shallow groundwater nutrient concentrations, although the exact reasons for such variations remain unknown. A possible explanation would be the variations in groundwater hydrology, soil property, and septic tank leakage rate.

A negative correlation existed between NO_x–N and TKN as well as between NO_x–N and NH_4^+, whereas there was a positive correlation between TKN and NH_4^+. NO_x–N is produced naturally in soil and groundwater through the microbial process of nitrification which is the biological oxidation of $NH_4^+$to NO_x–N under aerobic soil conditions. As a result, an increase in NO_x–N concentrations will correspond to a decrease in the concentrations of TKN and NH_4^+. Data also showed that no linear correlations existed between K and other nutrients, indicating that the major sources of groundwater K may come from different pathways and biotic and abiotic mechanisms.

A positive correlation was found between redox potential and water level. A lower (or shallower) water level reduced the concentration of oxygen (which is the most important electrical acceptor) in the shallow groundwater system and thereby reduced the redox potential. TKN, NH_4^+, PO_4^{3-}, and TP had negative correlations with redox potential, whereas NO_x had a positive correlation with redox potential. There was no correlation between K and redox potential. As the redox potential increased, more dissolved oxygen was available in the groundwater and surrounding soil for the oxidation of TON and NH_4^+ (noted that TKN = NH_4^+ + TON) into the reduced forms of nitrogen such as NO_2. As a result, the concentrations of TK and NH_4^+decreased as the redox potential increased. The sorption behavior of P is redox-sensitive and the bound P may be remobilized in periods with low redox potential. Therefore, an increase in redox potential would immobilize P in soils. The fate of K in the soil and groundwater is controlled mainly by cation exchange and not the redox potential. Thus, no correlation existed between redox and K in groundwater.

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