Nitrate contamination in private wells in rural Alabama, United States

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Abstract

Nitrate–N (NO₃⁻–N) concentrations in random water samples from rural residential wells in Alabama, USA, were analyzed over an 8-year period from 1992 to 1999. Data collected included land use, well depth, septic tank use and distance from the well and also livestock and cropping activities around wells. Of 1021 available data sets, 36% of samples showed nitrate–N concentration of higher than 1.0 mg/l, indicating the possible influence of anthropogenic activities. About 1.7% of samples had a nitrate–N concentration of higher than 10 mg/l. Results indicate nitrate contamination in groundwater was relatively low and stable in Alabama. Logistic regression analysis indicated that well depth, pH, and cropping activity were factors of statistical significance in influencing nitrate–N concentration in these wells. Factors such as septic tank use and livestock activities did not show a close link to nitrate–N concentration in wells tested.

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1. Introduction

In many parts of the world, groundwater is the only source for drinking water and domestic use. In Alabama, USA, about 20% of the population uses private wells for their potable water supply. More than 50% of Alabama residents use groundwater as the drinking water source. Seventy-four percent of the public water-supply systems in the state rely completely or partially on groundwater (USGS, 1990). Groundwater contamination, as a result of human activities, reduces the supply of safe drinking water and poses a public health threat. NO₃⁻–N occurs naturally in groundwater but can be harmful to the environment and human health at elevated concentrations (Harrison, 1992).

The background nitrate–N content of most groundwater sources is below 0.1 mg/l, although a few sources have been found to contain as much as 3.0 mg/l. The Maximum Contaminant Level (MCL) for nitrate–N as set by US EPA under the Safe Dinking
Water Act is 10 mg/l (US EPA, 1996). Unlike water from wells of public systems, private residential wells are not systematically tested for contamination. Agricultural fertilizer application, animal farming, septic tank uses, atmospheric deposition, and industrial and wastewater discharges, are the potential sources of groundwater contamination (Aelion and Conte, 2004). Nitrate from such sources can be introduced into surface and groundwater systems via runoff and infiltration (Limbrick, 2003). Nitrate, due to its high water solubility, is possibly the most widespread groundwater contaminant in the world, imposing a serious threat to drinking water supplies and promoting eutrophication. High NO$_3^-$ contamination of groundwater is found mainly in agricultural regions as a result of the widespread application of fertilizers and animal manure to agricultural land (Maticic, 1999; Vinten and Dunn, 2001). The use of inorganic fertilizers is widely suspected to be the most important factor (Oakes et al., 1981; Roberts and Marsh, 1987; Heathwaite, 1993).

The state of Alabama has a diverse subsurface environment that contains large quantities of groundwater (USGS, 1990). Major sand and gravel aquifers exist in the Coastal Plain while significant karst limestone and fractured rock aquifers cover the Tennessee Valley and the Ridge and Valley. The Cumberland Plateau and the Piedmont Provinces have less productive aquifers, but they are still important sources of supply to rural residential users. Recharge areas in Alabama cover 80% of the state and are vulnerable to contamination entering from the surface (USGS, 1990). Many private wells are used to provide potable water for residences throughout Alabama. Most of them are shallow wells of less than 30 m in depth. Because of their depth, these wells are often quite susceptible to contamination from anthropogenic activities (Aelion and Conte, 2004).

The purpose of this research was to monitor the quality of drinking water from wells used by rural residents and to identify the major risk factors affecting the nitrate concentrations. A broader goal is to develop an effective management program to protect the groundwater as one of critical sources of drinking water for rural residents. In this paper, we report results of nitrate–N concentration in private wells for an 8-year period from 1992 to 1999. Factors including the depth of wells, pH of water, septic tank use, livestock operations, and cropping activities around wells were examined for their correlation to corresponding nitrate–N concentrations. Statistical analyses using logistic regression were performed to delineate the significance of each factor in terms of its effect on nitrate–N concentration. Results indicate that well depth, pH, and cropping activity are significantly related to NO$_3^-$–N concentration in well water. However, septic tank uses and animal farming are found insignificant in influencing nitrate–N concentration in well water.

2. Methodology

2.1. Sampling and data collection

Water samples were collected in cooperation with the Alabama Cooperative Extension System. Water sampling bottles (250 ml) and survey forms were distributed by county extension agents in their respective counties and also at annual farmers’ conference held at Tuskegee University campus. The survey form was used to encourage rural residents to collect and send their well water samples to the Tuskegee water laboratory for analysis. At the same time, the survey form was designed to collect data such as land use, agricultural activities, purpose of water use, and well depth. It included a brief instruction on how to handle the sample, where to obtain the clean water sampling bottles, and the water quality parameters to be tested. It specifically requested individual resident to provide information such as water source (private well or public water system), the depth of water well, location where water was taken, land use such as cropping or animal farming operation, septic tank uses and distance from water well, and pesticide uses or storage. During an 8-year period from 1992 to 1999, more than 1400 water samples together with survey forms were received and processed. Residents were notified of the test results and were encouraged to contact the local public health agency and/or county agents if maximum contamination level was exceeded.

Prompt delivery of water samples was strongly encouraged. In most cases, it took 2 to 3 days for the delivery. Samples were analyzed on the day of receipt if possible. Otherwise, samples were stored at ~4 °C.
overnight. All data were put in a database for record and analysis.

2.2. Chemical analysis

A Hach DR/4000U spectrophotometer (Hach, Loveland, CO) was used to determine the NO$_3^-$–N and NO$_2^-$–N concentrations using the cadmium reduction method (Hach user manual, #8171). The standard calibration and sample preparation procedures were strictly followed. NO$_2^-$–N concentrations (mg/l) were quantified using the diazotation method (#8040). Preliminary tests showed a negligible concentration of NO$_2^-$–N for most well water samples. Therefore, no further NO$_2^-$–N tests were made for later samples and the total concentration of NO$_3^-$–N and NO$_2^-$–N measured by cadmium reduction method was generally referred to as NO$_3^-$–N concentration. NO$_3^-$–N quantification was based on standard curves that was calibrated in a range of 0–5 mg/l NO$_3^-$–N with a detection limit of 0.01 mg/l. Samples with NO$_3^-$–N of higher than 5 mg/l were diluted with deionized water prior to measurement.

2.3. Data analysis

Logistic regression was applied to predict a dependent binary response of NO$_3^-$–N concentration to independent variables that were identified as potential risk factors affecting NO$_3^-$–N concentration in well water. This statistical analysis was designed to evaluate anthropogenic factors that might significantly affect NO$_3^-$–N concentrations from well water. Factors included in the regression analyses and a brief description of each are listed in Table 1. NO$_3^-$–N concentration was used as a dependent variable and converted to a binary response of 0 or 1. The value of NO$_3^-$–N was designated “1” if the sample had NO$_3^-$–N concentrations of $\geq$1.0 mg/l; otherwise “0”. This arbitrary designation is based on an assumption that background concentration of NO$_3^-$–N is usually less than 1.0 mg/l (Aelion and Conte, 2004). Independent variables include the well depth, the septic tank uses, the livestock and cropping activities. The value of well depth was used as reported by residents; pH was used as measured in the laboratory; the septic tank uses was assigned “1” if there was septic tank, otherwise “0”. Similar conversions were applied to livestock and cropping activities (Table 1). Possible interrelation between factors was neglected due to the limited available information. The relatively large data size enabled us to simultaneously analyze the factors because the number of independent variables was far less than $m/10$, where $m$ is the number of data sets (Harrel et al., 1996). An independent variable is considered significant if it has a $p$, the value for Wald chi-square statistic with respect to a chi-square distribution, of less than 0.05 (95% confidence); and the upper and lower 95% confidence interval does not straddle 1.

Maximum likelihood estimation (MLE) was used to calculate the logit coefficients. Data sets used in logistic analysis must include all risk factors as discussed above. A total of 616 from more than 1400 sets of data satisfied above requirements and were chosen for the statistical analyses.

3. Results and discussions

3.1. Sampling locations and data description

Fig. 1 shows the locations from where residents submitted the water samples for analyses. The map was generated using the postal code from each sender. Symbols of different size and form are used to represent the range of total numbers of water samples from locations with same postal code. The sampling sites covered almost all counties in the state of Alabama although the overall sampling was random.

| Table 1: Variables and values used in logistic regression |
|----------|-----------------|------------------|
| Dependent variable | NO$_3^-$–N concentration | “1” if NO$_3^-$–N $\geq$1.0 mg/l |
|               | $(n=616)$        | “0” if NO$_3^-$–N $<1.0$ mg/l |
|               | $(n=197)$        | “0” if no septic tank use |
|               | $(n=419)$        | “0” if no livestock |
| Indep- | $W_d$ (Well Depth) | Resident reported value (m) |
| endents |               | “1” if septic tank used |
| $S_i$ (Septic tank use) | $(n=551)$ | “0” if no septic tank use |
|               | $(n=65)$        | “0” if no livestock |
|               | $A_n$ (livestock) | “1” if any livestock $(n=210)$ |
|               | $(n=406)$       | “0” if no livestock |
|               | $C_i$ (Cropping) | “1” if any cropping activity $(n=247)$ |
|               | $(n=369)$       | “0” if no cropping |
| pH          | Measured in laboratory |
and depended on the individual resident concern. In most cases, there were less than 16 samples sent from an area with same postal code. Relatively, there were more water samples sent from Birmingham and Montgomery areas. This might be due to the relatively higher population density in these areas.

Among more than 1400 samples, there were 1021 recorded NO$_3^-$–N data. An arbitrary range was set to characterize the histogram of all NO$_3^-$–N data (Fig. 2). The frequency (bars) and cumulative (line) of occurrence was correlated to each range of concentration of NO$_3^-$–N. Approximately 30% of water samples had NO$_3^-$–N concentrations between ≥0.1 ppm and <0.5 ppm. More than 50% of samples had less than 0.5 mg/l NO$_3^-$–N. 36% of the samples showed NO$_3^-$–N concentration of ≥1.0 mg/l, indicating possible effects of anthropogenic activities. In total, more than 98% of the samples had NO$_3^-$–N concentration of less than 10 mg/l, the US drinking water standard. The mean and median NO$_3^-$–N concentrations were 1.5 and 0.5 mg/l, respectively. A few samples (0.2%) were found to have NO$_3^-$–N concentration of ≥50 mg/l. The maximum NO$_3^-$–N concentration was 118 mg/l. The occurrence of these
high NO$_3^–$–N concentrations was randomly distributed in Alabama. The individual residents were notified of analysis results and encouraged to contact the local public health agency if elevated level of NO$_3^–$–N was found.

### 3.2. Statistical analyses of major factors affecting NO$_3^–$–N concentration in private well water

The variables identified as potential risk factors were summarized in Table 1. Data from survey questions were summarized and converted for logistic analysis if necessary. Samples with unanswered survey questions were excluded from logistic analysis. There were a total of 616 sets of usable data for the logistic analysis. Results of logistic regression are shown in Table 2. Two standards, $p$ is less than 0.05 (95% confidence) and the upper and lower 95% confidence interval does not straddle 1, was applied to estimate significance of each risk factor. It was found that three independent variables—well depth, cropping activity and water pH—showed significant influence on NO$_3^–$–N concentration. The negative coefficients for well depth and pH mean that a decrease in well depth or pH will result in an increase in the possibility of well waters with higher NO$_3^–$–N concentration. Similarly, a positive coefficient for cropping activities indicates an increased possibility of higher NO$_3^–$–N concentration for the well water if cropping activities exist around water well. The other two independent variables, septic tank use and presence of livestock, did not show significant effect (at 95% confidence) on NO$_3^–$–N concentration in well water.

Our survey results showed that most septic tanks (more than 50%) were in the range of approximately 15–60 m from water wells. Lack of significant effect of septic tank use on the concentration of NO$_3^–$–N indicates low possibility of direct diffusion of contaminants through soil column from septic tanks to water wells. Cautions should be taken when interpreting the statistical results. Our survey showed that more than 92% of residents who sent water samples reported septic tank use. Possibility exists

![Histogram of nitrate–N concentration](image)

**Fig. 2. Histogram of nitrate–N concentration.**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>S.D.</th>
<th>Coeff</th>
<th>SE</th>
<th>$p$</th>
<th>OR</th>
<th>Low95%</th>
<th>High95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_d$ (m)</td>
<td>59</td>
<td>75</td>
<td>-0.0080</td>
<td>0.0031</td>
<td>0.0096</td>
<td>0.99</td>
<td>0.986</td>
<td>0.998</td>
</tr>
<tr>
<td>$S_t$</td>
<td>0.92</td>
<td>0.27</td>
<td>0.15</td>
<td>0.51</td>
<td>0.77</td>
<td>1.2</td>
<td>0.42</td>
<td>3.2</td>
</tr>
<tr>
<td>$A_n$</td>
<td>0.37</td>
<td>0.48</td>
<td>-0.079</td>
<td>0.28</td>
<td>0.78</td>
<td>0.92</td>
<td>0.53</td>
<td>1.6</td>
</tr>
<tr>
<td>$C_t$</td>
<td>0.44</td>
<td>0.50</td>
<td>0.58</td>
<td>0.27</td>
<td>0.033</td>
<td>1.8</td>
<td>1.1</td>
<td>3.0</td>
</tr>
<tr>
<td>pH</td>
<td>6.9</td>
<td>1.0</td>
<td>-0.98</td>
<td>0.15</td>
<td>0.0018</td>
<td>0.38</td>
<td>0.28</td>
<td>0.50</td>
</tr>
</tbody>
</table>

* SD—standard deviation; Coeff—coefficient of logistic regression; SE—standard error; $p$-value for Wald chi-square statistic with respect to a chi-square distribution; OR—odds ratio; Low95% or High95%—upper and lower confidence levels.
that lack of comparable data without septic tank use might shield off the effect of septic tank use on ground water quality. Similarly, that the presence of livestock did not show a close link of statistical significance to NO$_3^{-}$–N concentration in well water might be due to low animal density. Most of residents responded to our survey reported only dogs or other domestic pet animals and still counted as “1”. The majority of rural residents in Alabama do not own large animal farms. Possible interrelations between independence variables were neglected. For example, use of fertilizers or pesticides due to the cropping activity may result in lower pH if well water was contaminated. Statistically, effects of other factors can be shielded off due to more direct correlation between factors such as pH and NO$_3^{-}$–N concentration. To eliminate this possibility, trial runs of regression on combinations of different independent variables were performed and similar results were obtained.

Lake et al. (2003) have pointed out that the transport of contaminants by surface diffusion through the soils greatly depends on geological factors. These factors include soil characteristics which may attenuate the NO$_3^{-}$–N pollution or lead to horizontal water movement and affect surface leaching; Drift cover which determine the permeability of superficial deposits such as glacial tills and alluvial silts and clays that may form an impermeable cover impeding the movement of water to the underlying aquifer; and aquifer type (Kelly, 1997). Therefore, our discussions are limited to effects of land uses because these detail geological data are largely unavailable for the private wells.

3.3. Temporal variation of NO$_3^{-}$–N concentration

The annual mean and median values of NO$_3^{-}$–N concentration for samples during the 8-year period are presented in Fig. 3a. A trend of increase in NO$_3^{-}$–N concentrations of both the mean and median values was observed starting 1992 and reached a peak around 1994. Following the peak was a downward trend of decrease in NO$_3^{-}$–N concentration from approximately 1996 to 1997. After that, there was a trend of increase until 1999 when this monitoring program was suspended. The seasonal variability was evaluated by monthly average value of NO$_3^{-}$–N concentration (Fig. 3b). The bars represent the monthly average that was calculated separately for each year during the 8-year period from 1992 to 1999; the solid line represents the overall monthly average for the whole 8-year period. Larger variation of monthly average for each year was observed and specific pattern of seasonal variation in NO$_3^{-}$–N concentration was hardly distinguishable. However, there was a general trend of gradual decrease in terms of overall monthly average of NO$_3^{-}$–N concentration (solid line) during the spring seasons approximately from January to May. NO$_3^{-}$–N concentration showed an increase starting the summer season between May and June and remained at a relatively stable elevated level until August. It was also observed that a decrease occurred during September and a higher concentration in October followed by a decrease during the short winter time of November and December.

We suspect that these variations as shown in Fig. 3a and b may be related to the seasonal and annual variation of rainfall as well as agricultural activities (Hallberg, 1987). In order to facilitate the discussion, an average monthly precipitation was calculated based on precipitation data for the state of Alabama during the period of 1971 to 2000 (National Climate Data Center of NOAA) and presented in Fig. 3b by the dashed line. It shows that more precipitation occurred during two periods, one was approximately from December to April and the other was from June to August. The lowest precipitation seasons occurred during the fall season from September to October. Comparing the average monthly precipitation data (dashed line) and the overall monthly average of NO$_3^{-}$–N concentration in well water (solid line), it seems that during the spring and summer season a higher precipitation was corresponding to relatively higher NO$_3^{-}$–N concentration in well water. However, contrary to the above observation, the correlation between the precipitation and NO$_3^{-}$–N concentration during September and October was reversed, i.e., a wet September and dry October corresponded to a lower and higher NO$_3^{-}$–N concentration in well water, respectively. The phenomena can be tentatively explained by agricultural activities. It is known that fertilizer application was more concentrated during spring and summer seasons when more nutrients were needed for planting and growing. Runoff
water due to the rainfall might carry NO$_3^-$–N from fertilizer and diffuse into the wells or recharge into aquifer to cause a higher NO$_3^-$–N well water. However, Agricultural activities diminish towards fall season and further increase in precipitation results in effects of flushing of aquifer or dilution of well water by the rainwater (Iqbal, 2002) to cause lower NO$_3^-$–N concentration. Similarly, the dry season can result in concentration of contaminants in well water (Vinten and Dunn, 2001; Pauwels et al., 2001).

### 3.4. NO$_3^-$–N Concentration vs. independent variables

Beyond water well depths and measured pH values, our survey also requested residents to report an estimated ranges of distance between water wells and septic tank, distance from well to animal farm or house, and distance from crop land. Fig. 4a–e graphically illustrated relations between NO$_3^-$–N concentration and these variables. It can be seen from Fig. 4a that a deeper water well most possibly has a lower NO$_3^-$–N concentration. Similarly, as
shown in Fig. 4b, well water was more likely to have lower NO$_3^-$-N concentration when water pH was higher. However, the distances between the water well and the three possible contamination sources did not show a recognizable effect on NO$_3^-$-N concentration (Fig. 4c–e). These observed phenomena are in agreement with the results of logistic regression.
4. Conclusions

An 8-year period monitoring of NO$_3^-$–N concentration from random samples of well water has shown that NO$_3^-$–N contamination was relatively low and stable in Alabama. Logistic analyses had shown that cropping activities are the major contributor to NO$_3^-$–N contamination in ground water; and that shallow wells are more susceptible to NO$_3^-$–N pollution. A deep well provides better protection for drinking water against NO$_3^-$–N contamination. Both annual and seasonal variations in NO$_3^-$–N concentration are possibly more related to precipitation and agricultural activities. Site specific investigations including detailed geological surveys will be required to establish an analytical model to quantitatively predict the effects of each factors.

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