# STATISTICAL ANALYSIS OF RURAL WELL CONTAMINATION AND EFFECTS OF WELL CONSTRUCTION

T. D. Glanville, J. L. Baker, J. K. Newman

**ABSTRACT.** *A previous statewide survey showed that 14% of rural wells in Iowa contained detectable concentrations of pesticides. To determine if improved private well construction regulations should be included in Iowa's State Pesticide Management Plan, a two-year study was undertaken to determine: the effects of well construction on pesticide, nitrate-nitrogen, and bacterial contamination of wells; and the possible role of point sources of contamination. Eighty-eight rural water supply wells in nine Iowa counties were sampled daily for five weeks during late spring and summer of 1993, and 20% of these were resampled in 1994. Short-term variation in nitrate-nitrogen concentrations was examined as a possible indicator of rapid inflow of shallow groundwater associated with well construction defects. Mean total coliform bacteria, nitrate-nitrogen, chloride, atrazine, alachlor, and metolachlor concentrations were statistically analyzed to determine if they were correlated, and t-tests also were used to determine if these water quality parameters were affected significantly by physical well parameters such as depth, type of casing, grouting, location within frost pits, and proximity to various potential sources of contamination. Study results indicate that: short-term water quality fluctuations, by themselves, were not a reliable indicator of deteriorated or improperly constructed wells; although the magnitude and frequency of positive total coliform test results was noticeably higher in shallower wells, a substantial fraction (21%) of wells greater than 30.5 m (100 ft) deep also had positive coliform results; t-tests and correlation analysis failed to show significant differences in mean atrazine or alachlor concentrations when comparing "shallow" and "deep" wells; increased well depth, by itself, did not ensure water supply protection from chemical or biological contaminants; mean nitrate-nitrogen and mean chloride concentrations had the strongest correlation (R = 0.57, p = 0.0001) among any of the contaminants tested; and mean atrazine and alachlor concentrations correlated moderately well with those for the more highly-mobile nitrate-nitrogen and chloride.* ***Keywords.*** *Atrazine, Alachlor, Metolachlor, Nitrate, Chloride, Wells.*

Pesticide and nitrate contamination of rural wells, and potential causes of such contamination, have been the topic of several large-scale research projects conducted in the past 10 years. Based on results of its five-year national survey of pesticides in drinking water wells, the USEPA (1990) estimated that 4.2% of 10.5 million rural domestic wells in the U.S. contain at least one pesticide, and that 2.4% of rural wells contain nitrate-nitrogen at or above the maximum contaminant level* (MCL). Likewise, a study of 1,430 rural wells in 26 agricultural states (Monsanto, 1990) showed that: nitrate-nitrogen concentrations exceeded the MCL in 4.85% of wells sampled; and that detectable concentrations of atrazine, alachlor, and metolachlor were present in 11.68%, 0.78%, and 1.02% of these wells, respectively. More recently, analysis of well water samples voluntarily submitted by rural well users in 17 states showed that: 3.9% of more than 43,000 samples tested exceeded the MCL for nitrate-nitrogen; 9.8% of 14,044 samples analyzed for pesticides contained detectable concentrations of triazine herbicides; and alachlor, alachlor breakdown products, or metolachlor were detected in 7.4% of 12,539 samples (Baker et al., 1994). Similar results also have been reported by Rudolph and Goss (1992, 1993) based on samples drawn from 1,300 domestic farm wells located throughout Ontario, Canada. In this case, 13 to 15% of the farm wells tested exceeded the MCL for nitrate-nitrogen, and 8 to 12% contained detectable concentrations of one or more of six herbicides or herbicide metabolites (alachlor, atrazine, cyanazine, metribuzin, metolachlor, and deethyl atrazine).

While public health officials and well drillers often cite poor well construction, well deterioration, and point-sources of contamination as key factors contributing to rural well contamination, some groundwater studies suggest that local geologic conditions are a more important determinant of well water quality. As policy makers with the Iowa Department of Agriculture and Land Stewardship began the task of developing a Statewide Pesticide Management Plan in accordance with EPA directives, the question of whether or not improved private well construction regulations should be a part of this plan lead to a two-year study of private well construction and it's effects on water supply contamination.

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* Maximum contaminant level (MCL). The maximum concentration of a contaminant permitted by USEPA regulations in water delivered to any user of a public water system.

  

## Study Methods

Study methods included: (1) daily sampling of 88 private wells to determine if contaminated wells exhibit greater short-term water quality variability (suggestive of casing leakage) than wells with little or no contamination; (2) statistical analyses of potential relationships between well (or site) characteristics and water quality; (3) groundwater monitoring in the vicinity of contaminated water supply wells to determine if the quality of water they deliver differs significantly from local groundwater quality; (4) intensive sampling during an eight-hour period of continuous pumping, to determine if day-to-day variability is affected by time of sampling; and (5) ponding of chloride tracer solution around contaminated water wells to determine if such a test can detect well defects leading to contamination. Results of study phases 1 and 2 are presented here. Results from phases 3 through 5 are presented in an article currently in preparation.

### Well Selection

To insure that the water supply wells in this study represented a variety of construction types, depths, and local geologic conditions, the study area was selected to include nine counties† located in five distinct hydrogeologic regions defined by the Geologic Survey Bureau of the Iowa Department of Natural Resources. County environmental health sanitarians in each county were asked to identify at least five prospective project cooperators having "problem" wells (based on previous nitrate-nitrogen, total coliform bacteria, and/or pesticide tests), and another five individuals with wells that had not exhibited water quality problems.

### Water Sampling and Analysis

Thirty to thirty-five daily samples were collected from each study well during late spring and/or summer of 1993. Samples were collected by well owners and held in refrigerated storage until project personnel could transport them to the laboratory. At least five samples from each well were tested for atrazine, nitrate-nitrogen, and chloride, and at least two of these five samples also were analyzed for alachlor and metolachlor. Based on these preliminary results, as many as 15 to 20 additional samples were tested from wells exhibiting elevated or highly variable nitrate-nitrogen or pesticide concentrations. Each project well also was sampled twice for total coliform bacteria.

All sample collection, storage, and analysis was conducted in accordance with an EPA-approved Quality Assurance (QA) Plan. To keep analytical costs within the project budget, pesticides were quantified using enzyme-linked immunosorbent assay (ELISA) materials and procedures developed and marketed by Omicron.

† Counties in the study included: Cherokee, Sac, Bremer, Winneshiek, Linn, Jackson, Guthrie, Page, and Humboldt. Study wells are identified by the first letter of the county where the well is located, and a number (e.g., W9).

## Well Characteristics and Water Quality Analyses

### Hydrologic Conditions During Study

Statewide precipitation in Iowa during the first eight months of 1993 was the highest in 121 years of record. The period from May through August of 1993 was characterized by widespread flooding that severely delayed or greatly reduced applications of the herbicides targeted for analysis. In light of these abnormal conditions, it was subsequently decided to resample approximately 20% of project wells in 1994 to evaluate the extent to which the 1993 results were biased by the unusually wet weather.

### Well Age and Type of Construction

Three of the 88 wells included in this study were drilled prior to 1900, and 20 were constructed during or after 1990. Well depths ranged from 6.0 to 152.4 m (20 to 500 ft) deep. Newer wells showed a trend toward greater depth;15% of the wells constructed prior to 1971 were more than 45.7 m (150 ft) deep while 35% of wells constructed after that time exceeded this depth (fig. 1).

Fifty-one percent (51%) of study wells were constructed with steel casing, 15% were cased with plastic, and approximately 23% of study wells were cased with concrete tile. These proportions compare favorably with those reported by Kross et al. (1990) in a statewide study of 686 randomly selected private wells in Iowa.

### Type, Frequency, and Concentration of Well Contaminants

**Chemical Contaminants.** The non-random well selection technique used in this study resulted in a substantially higher frequency of herbicide detections among the study wells than would be expected from a purely random sampling of private wells (table 1). Use of

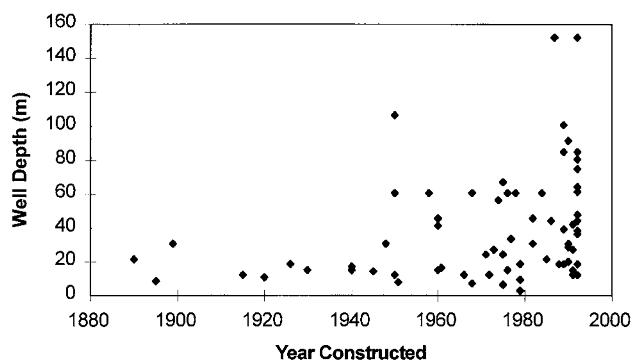


**Figure 1–Well depth vs year constructed.**

**Table 1. The 1993 water quality test results compared with 1988-89 statewide sampling**

| Parameter | Study Wells with Detections | Maximum Mean Value* | MCL or HAL | % of Study Wells with Mean > MCL or HAL | % of Wells in Previous Statewide Study with Herbicide Detections or $NO_3$-N>10 mg/L† |
|---|---|---|---|---|---|
| Atrazine | 39.8% | 6.38 ug/L | 3 ug/L | 1.1% | 8.0% |
| Alachlor | 22.7% | 2.81 ug/L | 2 ug/L | 1.1% | 1.2% |
| Metolachlor | 4.6% | 0.24 ug/L | 100 ug/L | 0.0% | 1.5% |
| Nitrate-N | —- | 41.6 mg/L | 10.0 mg/L | 34.1% | 18.3% |

* Value for well having the highest mean concentration.
† Based on 1988-89 Statewide Rural Well Survey of 686 randomly selected wells (Kross et al., 1990).

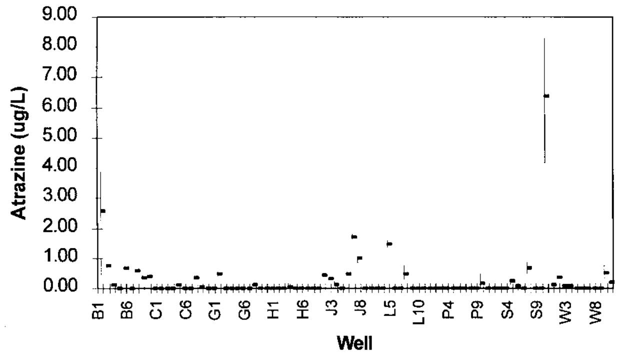


**Figure 2–Mean (-) and range of atrazine detected in study wells (1993).**

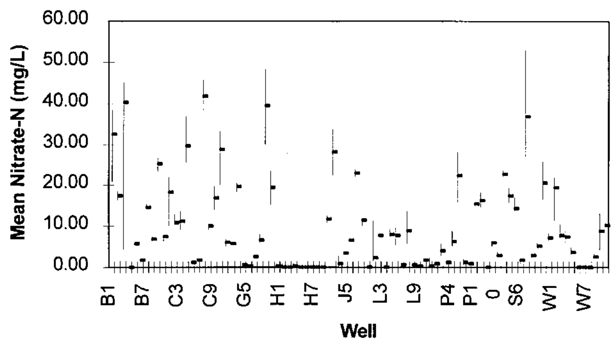


**Figure 3–Mean (-) and range of nitrate-nitrogen in study wells (1993).**

ELISA test procedures, which usually respond, to some extent, to metabolites as well as to the parent compound, also may have increased the frequency and magnitude of herbicide detections. Despite these factors, only about 1% of the study wells exhibited mean herbicide levels exceeding an MCL or health advisory level‡ (HAL). The percentage of wells in this study exhibiting mean nitrate-nitrogen concentrations exceeding the MCL was much higher than observed in a random sampling of rural wells in Iowa conducted by Kross et al. (1990). As illustrated in figures 2 and 3, some wells exhibited much more contaminant variability than others during the 4- to 5-week sampling period.

**Total Coliform Bacteria.** Twenty-five percent (25%) of study wells tested positive during the first round of total coliform sampling, as did 28% during the second round. Data from other studies (e.g., Kross et al., 1990) as well as that aggregated from samples voluntarily submitted to the University of Iowa Hygienic Laboratory by well owners each year suggest that 35 to 45% of private wells typically contain unsafe total coliform densities. Eight samples in the first round were rejected by the laboratory due to presence of chlorine apparently caused by inadequate rinsing of sample taps following disinfection with bleach solution. Statistical analysis revealed only moderate correlation (R = 0.33, p = 0.0007)§ between the first and second rounds of coliform test results. Studies by Rudolph and Goss (1992, 1993) have shown a similar lack of repeatability between consecutive coliform analyses from the same well.

‡ Health advisory level (HAL). The concentration of a contaminant in drinking water that is not expected to cause any adverse noncarcinogenic effects over a lifetime of exposure.

§ The "p" value associated with a correlation coefficient,"R", indicates the probability of obtaining that value for the coefficient, purely by chance, if no correlation actually exists. The smaller the p value, the less likely that no correlation exists (i.e., the more likely that the correlation is significant).

## CONTAMINANT CORRELATIONS

Two types of correlation analyses were conducted. Correlations among mean contaminant concentrations for each well provide an overview of the co-occurrence of various contaminants across a variety of well types and geologic settings throughout the 30-day sampling period. Correlation analyses of daily contaminant concentrations for individual wells also were performed. These statistics indicate how concentrations of different analytes vary within a given well over short time spans.

The strongest correlation (R = 0.57, p = 0.0001) among mean contaminant concentrations occurred between chloride and nitrate-nitrogen (table 2). Chloride concentrations also exhibited a moderate association with alachlor (R = 0.38, p = 0.0004), and a somewhat weaker association with atrazine (R = 0.23, p = 0.0405). While chloride occurs naturally in some groundwater, positive correlation with nitrate-nitrogen and pesticides suggest that at least a portion of the chloride detected in this study originated above ground (e.g., in rainwater, fertilizers, road deicing agents, or household wastewater) and may have traveled similar flow paths with other surficially derived contaminants.

Mean concentrations of alachlor and atrazine, the two pesticides found most frequently in well water samples, showed relatively good correlation (R = 0.44, p = 0.0001). This was the second highest correlation among contaminants, and is thought to reflect their widespread (and possibly simultaneous) use and similar leaching potentials. Mean nitrate-nitrogen concentrations also correlated moderately well with mean atrazine (R = 0.38, p = 0.0003), and to a lesser extent with mean alachlor concentrations (R = 0.32, p = 0.0020). These statistics indicate that high nitrate-nitrogen concentrations are a good indicator of the potential for pesticide detections, but that nitrate-nitrogen, by itself, is only a marginal predictor of pesticide concentrations.

Like the correlations among mean contaminant concentrations, correlations of contaminant concentrations in individual daily samples generally were positive. Some wells, however, did not follow this trend. Daily samples from the well designated as S10, for example, showed a strong positive correlation between nitrate-nitrogen and chloride, but the correlation between daily nitrate-nitrogen and atrazine was strongly negative (R = –0.92, p =

**Table 2. Correlations among mean contaminant values**

| | Atrazine | Alachlor | Chloride | Nitrate-nitrogen | Coliform Round No. 1 | Coliform Round No. 2 |
|---|---|---|---|---|---|---|
| | ---Correlation Coefficient (r)--- | | | | | |
| Atrazine | 1.00 | 0.44 | 0.23 | 0.38 | –0.14 | –0.06 |
| Alachlor | | 1.00 | 0.38 | 0.32 | –0.07 | –0.04 |
| Chloride | | | 1.00 | 0.57 | 0.25 | 0.11 |
| Nitrate-nitrogen | | | | 1.00 | 0.02 | 0.27 |
| Coliform 1 | | | | | 1.00 | 0.33 |
| Coliform 2 | | | | | | 1.00 |

0.0005). Interestingly, well S10 had the highest levels of atrazine of any well in the study (mean concentration = 6.38 µg/L). These levels are much higher than found in any other well, suggesting that point source contamination is likely. If this is the case, then negative correlation between nitrate-nitrogen and a pesticide may signal a characteristic difference between contaminants originating from diffuse sources and those emanating from more concentrated sources.

Like S10, well L7 exhibited negative correlations between daily nitrate-nitrogen and pesticide concentrations, and nitrate-nitrogen also correlated negatively with chloride. Well L7 is a 61 m (200 ft) bedrock well with a history of water quality problems associated with poor casing installation at the time of its construction in 1992. This well has since been abandoned and replaced with a properly grouted well of nearly the same depth, and water quality has improved considerably. In light of its history, L7 appears to have been pumping shallow groundwater that made its way into the well via preferential flow paths rather than by matrix flow through overlying strata. If this is the case, the shift from positive correlations among mean analyte concentrations to highly negative correlations among daily values, may signal a preferential flow regime that can rapidly increase the presence of surficial contaminants in the well while simultaneously diluting certain other contaminants, like nitrate-nitrogen, that are typically picked up during matrix flow through the topsoil.

### Statistical Associations Between Well Characteristics and Water Quality

Previous attempts to statistically associate well contamination with well site or well construction characteristics have met with limited success (Hallberg et al., 1992; Koelliker et al., 1987; Koelliker et al., 1992; Baker et al., 1994; Rudolph and Goss, 1992, 1993). Most studies of this type, however, have been based primarily on random selection of wells and one-time sampling or a small number of samples collected on an infrequent basis. This study was designed to gain additional insights through daily sampling and comparison of responses observed in "problem" wells and wells that have not exhibited water quality problems.

**Well Depth.** Data collected during the first round of total coliform bacteria sampling showed about 14% of wells >30.5 m (100 ft) deep contained unsafe coliform levels while 33% of wells ≤30.5 m deep were found unsafe. A second round of coliform samples showed more frequent coliform problems, with 19% of wells >30.5 m deep and 34% of wells ≤30.5 m deep testing unsafe.

As shown in table 3, mean coliform densities in wells ≤30.5 m deep were significantly ($p = 0.008$) higher than in deeper (>30.5 m) wells. The same held true when wells ≤15.2m (50 ft) deep were compared with those >15.2 m deep, but the differences were not as pronounced ($p = 0.018$). Contrary to the trends suggested by average coliform densities in various depth classes, correlation analysis of data from individual wells failed to show a statistically significant relationship between coliform densities and well depth.

Frequency statistics for the 1993 data show that wells ≤30.5 m deep were only slightly more likely to contain atrazine than deeper wells. While atrazine was found in about 45% of wells ≤30.5 m deep, 32% of wells >30.5 m deep also contained it. Little difference was noted in the frequency of alachlor detections in various depth categories. About 20% of study wells above and below the 30.5-m depth contained this chemical in 1993. Metolachlor, which was detected in only four wells, was found only in wells ≤30.5 m deep.

T-tests comparing "shallow" (≤30.5 m) and "deep" (>30.5 m) wells showed no significant differences in mean atrazine or alachlor concentrations. Similar results were observed using a 15.2-m depth criterion, and correlations of pesticide concentrations with well depth were not significant.

Trends relating nitrate-nitrogen concentrations and well depth were strong (fig. 4). Sixteen percent (16%) of wells 30.5 m deep or greater had nitrate-nitrogen concentrations exceeding the MCL of 10 mg/L. In wells ≤30.5 m deep, 62% exceeded the MCL.

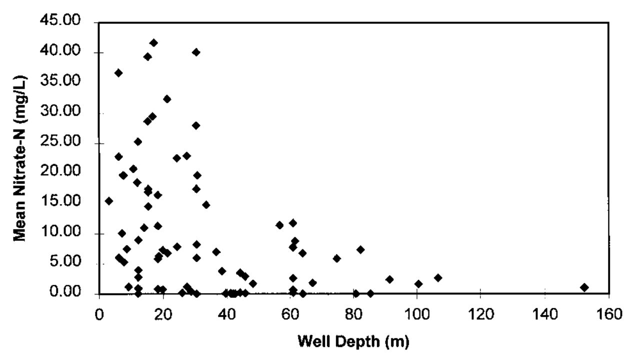


**Figure 4–Mean nitrate-nitrogen vs well depth (1993).**

**Table 3. T-tests comparing mean coliform levels in various well depth categories**

| Depth Interval | Sample Size (N) | Mean No. Organisms/100 mL in Second Round of Coliform Tests | Statistical Significance* |
|---|---|---|---|
| ≤15.2 m | 17 | 5.7 | |
| >15.2 m | 48 | 1.3 | p = 0.018 |
| ≤30.5 m | 38 | 3.7 | |
| >30.5 m | 27 | 0.8 | p = 0.008 |
| ≤15.2 m | 21 | 5.1 | |
| >61.0 m | 17 | 0.9 | p = 0.01 |

* "p" values of less than 0.01 indicate there is less than a 1% chance that mean coliform densities for the "shallow" and "deep" groupings differ as much as they do purely by chance.

**Table 4. T-tests for mean nitrate-nitrogen at various depths**

| Depth Interval | Sample Size (N) | Mean Nitrate-nitrogen (mg/L) | Statistical Significance |
|---|---|---|---|
| <15.2 m | 24 | 16.0 | |
| >15.2 m | 60 | 7.9 | p = 0.003 |
| <30.5 m | 47 | 15.2 | |
| >30.5 m | 37 | 3.8 | p = 0.0001 |
| <15.2 m | 24 | 16 | |
| >61.0 m | 21 | 3.5 | p = 0.0001 |
| <61.0 m | 63 | 12.5 | |
| >61.0 m | 21 | 3.5 | p = 0.0001 |

As shown in table 4, mean nitrate-nitrogen concentrations for various depth groupings showed highly significant differences between all "deep" and "shallow" groupings. Furthermore, a relatively high negative correlation (R = –0.43, p = 0.0001) between nitrate-nitrogen and well depth was found to be statistically significant.

**Well Grouting.** Twenty-six percent (26%) of the owners or users of the 88 study wells reported that their wells had been grouted. T-tests comparing mean contaminant concentrations revealed that only nitrate-nitrogen and chloride were significantly lower ($p \leq 0.01$) in wells reported to have been grouted. Multiple regression analysis, however, failed to show that grouting alone had a significant effect on water quality.

Failure to show significant relationships between water quality and grouting may be due to the fact that grouting data were obtained through interviews with well owners or users, not from drillers logs. Since many well owners don't have a thorough understanding of well construction, the accuracy of the grouting data is suspect. Furthermore, grouting practices are far from uniform among private water well contractors. As a result, some wells reported to be grouted may not be effectively sealed against entry of surface water or shallow groundwater.

**Well Type.** T-tests comparing bored wells (clay or concrete tile wells, mean depth 12.8 m) with drilled wells (steel or plastic casing, mean depth 47.2 m) indicated significantly lower mean nitrate-nitrogen concentrations (p = 0.04) in drilled wells. However, when the drilled well population was segregated according to casing material, nitrate-nitrogen concentrations in drilled wells with steel casing were not significantly lower than in the bored wells. Drilled wells with plastic casing, however, had significantly (p = 0.005) lower mean nitrate-nitrogen concentrations (4.5 mg/L) than bored wells (12.9 mg/L). Since plastic is a relatively new casing material that was not widely used in Iowa until the past 20 years, one might guess that the evidence of reduced nitrate-nitrogen in plastic wells may be due to greater well depth or a higher frequency of grouting. This was not the case, however, as only 33% of the 12 plastic wells (average age six years) were reported to have been grouted, and their mean and median depths were 37.2 m and 29.6 m, respectively. Though considerably older (mean age 25 years) 32% of the 44 steel wells were reported to have been grouted, and their mean (49.4 m) and median (41.5 m) depths exceeded those of the plastic wells.

Drilled and bored wells showed no significant differences in atrazine concentrations, and none of the 22 bored wells contained alachlor. Multiple regression analysis did not identify well type as a significant variable affecting nitrate-nitrogen or pesticide variability.

**Frost Pits.** Wells located in frost pits had significantly (p = 0.035) higher levels of nitrate-nitrogen (15.2 mg/L) than wells not located in pits (8.1 mg/L). Atrazine and alachlor concentrations for wells located in pits, however, were not significantly different from other wells. Wells located within frost pits also were categorized according to whether they exhibited evidence of pit flooding. Multiple regression analysis showed that flooded well pits do affect nitrate-nitrogen levels after eliminating interactive effects, but this accounts for only a small portion of the nitrate-nitrogen concentration variability among wells.

**Type and Proximity of Pesticide/Nitrogen Sources.** Group comparisons based on proximity to nitrogen sources and pesticide handling or use areas yielded illogical results suggesting that wells in close proximity to such activities have lower contaminant concentrations than more distant wells. Based on such results one must conclude that, although proximity to point sources has undisputed common sense implications for groundwater quality protection, pesticide handling and use practices are only a part of the total picture in predicting the likelihood of well contamination.

**Pesticide Spills/Accidents.** Interviews with well owners/users revealed that seven of the 88 study wells had a history involving pesticide back siphoning or spills. During the 1993 sampling program, pesticides were detected in only one of these seven wells. Atrazine was found in this particular well at 0.46 ug/L. The accident involving this well occurred 10 years earlier, and the persons interviewed could not recall the pesticide involved.

**Well Age.** T-tests comparing mean contaminant concentrations in wells less than and greater than various age levels (10, 25, and 50 years) all indicated significantly lower nitrate-nitrogen (p ranging from 0.0001 to 0.014) in newer wells. Surprisingly, significant differences were not noted for mean pesticide concentrations.

Correlation analysis showed age to be strongly correlated with nitrate-nitrogen concentrations (R = 0.45, p = 0.0001), and moderately correlated with mean atrazine (R = 0.36, p = 0.0016), mean alachlor (R = 0.35, p = 0.0025), and mean chloride concentrations (R = 0.29, p = 0.0138). No significant correlation could be seen between age and coliform levels.

While age was treated as a single variable in this analysis, it obviously is correlated with other physical characteristics reflecting the construction and condition of the well. Well age, for example, is inversely correlated with well depth (R = –0.32, p = 0.0071). Depth, in turn, is correlated inversely with well diameter (R = –0.53, p = 0.0001). As might be expected, older wells tend to be more shallow and also are inclined to be constructed from larger diameter tile casing. Both of these conditions are consistently associated with lower water quality.

## Long- and Short-term Water Quality Variability

Reports of sudden changes in turbidity or color of well water, often following an intense rainstorm, suggest that defects in some wells may be short-circuiting natural recharge processes. With this in mind, variability in daily water samples was examined to determine the extent to which short-term water quality variability occurs in private wells, and to assess its value as a possible indicator of defective well construction and the potential for well contamination.

**Comparison of 1993 and 1994 Water Quality Data.** In all but a few instances, rainfall recorded at the 18 project wells that were resampled in 1994 was substantially less than in 1993. Despite these precipitation differences, mean chloride concentrations in the majority of wells exhibited relatively little variation between years. A few wells (fig. 5) did exhibit chloride shifts, however, with G8 and S4 exhibiting noticeably higher mean chloride concentrations in 1993. Precipitation data at G8 confirms that this site experienced substantially greater rainfall in 1993 than in

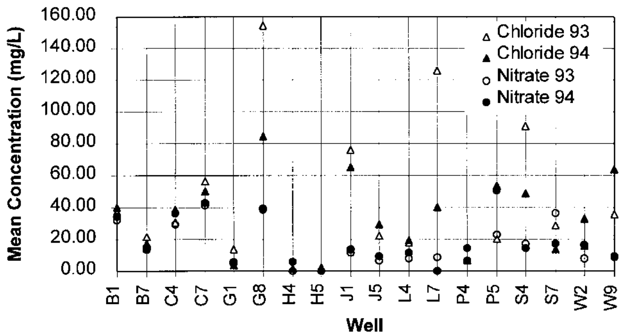


**Figure 5–Nitrate-nitrogen and chloride in wells sampled during both 1993 and 1994. (Note: 1994 data for well L7 reflect new well constructed at same depth).**

1994. Based on regional rainfall trends, it is believed that well site S4 experienced similar rainfall patterns but, since the cooperating well owners at site S4 were unwilling to collect daily rainfall data, this cannot be confirmed.

Unlike the chloride observations in wells G8 and S4, wells W2 and W9 in northeastern Iowa exhibited mean chloride concentrations in 1994 that were nearly twice the 1993 values. Since 1994 precipitation (during the sampling period) at site W9 was more than twice that reported in 1993, however, the trend of increased chloride concentration during sampling periods with higher rainfall appears to be similar to the observations at wells G8 and S4. As in the case of well S4, the cooperating well owners at site W2 were unwilling to keep daily rainfall records (these were the only two cooperators that did not keep daily rainfall records). So, although site W2 is located relatively close to site W9, it cannot be confirmed that rainfall during the 1994 sampling period at site W2 exceeded precipitation during the 1993 sampling period.

Unlike chloride, nitrate-nitrogen concentrations in most wells (fig. 5) were nearly the same in 1993 as in 1994. Mean atrazine and alachlor concentrations varied on a case-by-case basis exhibiting no obvious relevance to precipitation or year.

Samples from monitoring wells constructed near project wells G8 and S4 provide possible clues as to why chloride concentrations rose during wet weather and nitrate-nitrogen concentrations did not. Three monitoring wells were completed at each site: one was finished just below the water table, the second at the same depth as wells G8 and S4 (both reported to be 15.2 m deep), and the third at a depth midway between the first two monitoring wells. Monitoring well data indicated that shallow groundwater at both sites contained noticeably higher concentrations of chloride than was measured in wells G8 and S4 themselves. And, in both cases, wet weather lead to increased chloride concentrations in wells G8 and S4.

Although wells G8 and S4 produced water having nitrate-nitrogen concentrations two to four times the MCL, concentrations in the shallow monitoring wells were not substantially different from those in the water supply wells, and mean nitrate-nitrogen levels in the water supply wells were nearly identical during 1993 and 1994.

These contrasting responses to rainfall suggest that when contaminant concentrations at depths above the intake zone of the water supply well are higher than in the water supply well itself, wet weather can lead to increased contaminant concentrations in the water supply well. Conversely, when contaminant concentrations in shallow groundwater are not significantly different from those found in the water supply well, then contaminant concentrations are less likely to change during wet seasons.

**Short-term Water Quality Variation.** Several measures of short-term water quality variability were investigated to determine how rapidly well water quality changes occurred and whether the rate of change was relevant to well contamination. Since more samples were tested for nitrate-nitrogen than other contaminants, and since the nitrate-nitrogen test is more accurate than ELISA tests for pesticides, analysis of short-term variability was based on the nitrate-nitrogen results.

The standard deviation of nitrate-nitrogen in daily water samples was relatively low. Despite the fact that about one-half of the 88 project wells contained one or more contaminants (nitrate-nitrogen, pesticide, or total coliform), only about one-fourth of the wells sampled in 1993 exhibited standard deviations in daily nitrate-nitrogen concentrations greater than 1 mg/L during the 30-day sampling period.

Wells in Linn, Winneshiek, Jackson, and Bremer Counties, locations characterized by sinkholes and shallow bedrock which are conducive to natural groundwater quality variability, did not exhibit noticeably greater variability than wells at other locations. The most notable incidence of elevated nitrate-nitrogen variability (six of ten wells with standard deviations > 1 mg/L) occurred in Cherokee County, a western county where eight of ten study wells tap discontinuous sand and gravel deposited in till at depths of 18.3 m (60 ft) or less.

Short-term nitrate-nitrogen variability appears weakly related to mean water quality. Regression of standard deviation against the mean nitrate-nitrogen concentration showed that predicted nitrate-nitrogen standard deviations were more than twice the 5% maximum analytical error associated with the nitrate-nitrogen test. As indicated by a relatively low $R^2$ value (0.59), however, nitrate-nitrogen variability is not a strong predictor of mean nitrate-nitrogen concentrations.

When wells of similar depth are compared, those cased with steel or plastic were about as likely to exhibit elevated variability as wells cased with brick or concrete tile (fig. 6). With one exception, wells reported as having been grouted exhibited nitrate-nitrogen standard deviations of 1 mg/L or

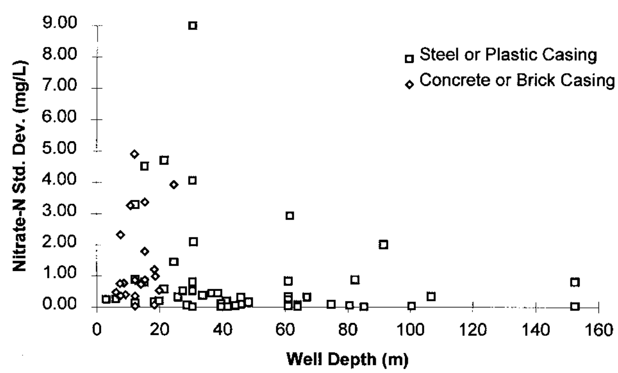


**Figure 6–Comparison of nitrate-nitrogen variability for wells with various casing types.**

less. This agrees with t-test results indicating significantly lower mean nitrate-nitrogen levels associated with grouted wells. As noted earlier, however, the majority of grouted wells were at least 30.5 m deep, making it difficult to conclude that grouting alone was the causative factor in reduced nitrate-nitrogen variability.

In an attempt to determine if the rate of nitrate-nitrogen fluctuation was a possible indicator of well defects, an index of fluctuation was derived by dividing the difference between maximum and minimum daily nitrate-nitrogen concentrations recorded for each well (in 1993) by the number of days that elapsed between their occurrence. Eleven of the 88 project wells registered average fluctuations of 1 mg/L/day or greater in 1993. Based on the results of tracer tests conducted during phase 5 of this study, however, this index of fluctuation did not appear to be a reliable indicator of defective wells. Well G8, for example, which showed no physical evidence of “short-circuiting” during an 8-h tracer study has the greatest index of fluctuation (18 mg/L/day). Well S7, which was shown to be extremely leaky during the tracer studies, had an index of fluctuation of less than 1 mg/L/day.

In general, contaminant variability was found to be lower in 1994 than during the relatively wet sampling period in 1993. As such, it appears that the measures of short-term variability that were explored in this study would have little utility as indicators of the contaminant transport mechanism or well condition during years of average or below average rainfall.

## Conclusions

Nitrate-nitrogen and chloride concentrations exhibited the strongest correlation (R = 0.57, p = 0.0001) among any of the contaminants tested. Since nitrate-nitrogen in Iowa groundwater generally is believed to originate from above-ground sources, the relatively strong positive correlation between chloride and nitrate-nitrogen suggests that at least a portion of the chloride in rural wells originates from above ground sources too.

The second strongest correlation (R = 0.44, p = 0.0001) occurred between alachlor and atrazine. Since both are moderately soluble and neither is strongly adsorbed on soil organic matter or rapidly degraded, it is reasonable that they could migrate together, and that their concentrations would rise and fall in concert when both are present.

Somewhat surprisingly, mean atrazine and alachlor concentrations correlated moderately well with concentrations of the more highly mobile nitrate-nitrogen and chloride. The fact that these chemicals tend to rise and fall in concert for a variety of geologic settings and well types suggests that many private wells are of insufficient depth to be adequately protected by sorption, degradation, and aquitard shielding, or that the construction of the wells themselves may permit preferential flow that bypasses the natural protection of the site. Either case calls for improved well design and construction.

Although statistical analyses of daily water quality data generally produced positive correlations in agreement with those noted between mean values of chloride and other contaminants, one well with an extremely high mean atrazine concentration (6.38 μg/L) exhibited a strongly negative correlation (R = –0.92, p = 0.0005) between daily nitrate-nitrogen and atrazine. Another well having a history of casing leakage also exhibited strongly negative correlations between nitrate-nitrogen and atrazine (R = –0.82, p = 0.0012) and between nitrate-nitrogen and alachlor (R = –0.96, p = 0.0001). These observations suggest that negative correlations between nitrate-nitrogen and a pesticide may signal the presence of a nearby point source of contamination, or preferential contaminant flow into a well.

The frequency of positive total coliform test results was noticeably higher in shallower wells, and t-tests comparing average coliform densities for wells in various depth classes confirmed significantly higher densities in shallower wells. Despite these general trends, however, coliform densities in individual wells did not correlate significantly with well depth, and a substantial fraction (21%) of wells >30.5 m deep had positive coliform results during the second round of testing. Preferential flow through defective casings or along the exterior of poorly grouted well casings seems a reasonable explanation for the presence of coliform bacteria in relatively deep wells.

T-tests and correlation analyses failed to show significant trends in the concentration of mean atrazine or alachlor with well depth. Clearly depth alone cannot ensure well protection because the geology of some areas, notably northeastern Iowa, is such that even relatively deep formations are vulnerable. At the same time, many regions do afford greater protection with increasing depth, and the presence of atrazine in 32% of study wells that are >30.5 m deep suggests that at least a portion of these are due to indiscriminate penetration of protective strata and failure to reestablish the protection through effective well grouting.

Unlike the pesticide data, the incidence of nitrate-nitrogen exceeding the MCL was substantially higher in shallow wells, and correlation analysis and t-tests also indicated increasing nitrate-nitrogen concentrations as well depth decreased. Widespread distribution of nitrate-nitrogen in the environment (hence a greater number of nitrate-nitrogen data points above the detection limit), and its high mobility in the soil (less reliance on preferential flow), may explain why nitrate-nitrogen concentrations exhibited distinct trends with well depth while the pesticide data did not.

Although wells reported as having been grouted tended to have slightly lower mean concentrations of nitrate-nitrogen, chloride, and pesticides, t-tests revealed that only nitrate-nitrogen and chloride were significantly lower in grouted wells. Unreliable grouting data may have partially obscured stronger relationships between grouting and contaminant concentrations.

Attempts to relate nitrate-nitrogen or pesticide concentrations to a well’s proximity to contaminant sources (septic tanks, leaching fields, feedlots, and pesticide mixing or application areas) produced no consistent or logical results. This should not be interpreted to mean that horizontal separation distances recommended by well drilling regulations are ineffective. The contaminant location data used in this study were derived through interviews with well owners and superficial observation of the well site by project field staff. Numerous uncertainties regarding past land uses, forgotten spills, buried wastes, location of waste treatment facilities and pipelines, and the construction of the well, make it difficult to define clear relationships between well water quality and contaminant sources.

Correlation analysis and t-tests both showed strong trends toward increased contaminant concentrations in older wells. Since older wells tend to be relatively shallow, are frequently constructed with leaky casing materials (brick or tile), and often are located close to potential sources of contamination, it is clear that well age is not a single variable but a composite of a several physical variables relevant to water quality.

Data from the 20% subsample of wells tested in both 1993 and 1994 showed that, in most cases, mean nitrate-nitrogen and chloride concentrations were only slightly higher during the wetter year (1993). Atrazine and alachlor levels were less consistent with some wells showing higher levels in 1993 and others in 1994. Various measures of short-term nitrate-nitrogen variability failed to show promise as indicators of poor well construction or well deterioration.

Based on results of this study, there appears to be sufficient justification to include improved well construction regulations as part of Iowa's State Pesticide Management Plan. Positive correlations between highly mobile contaminants, such as nitrate-nitrogen or chloride, and contaminants such as atrazine and alachlor that are more likely to be sorbed or degraded, suggests that many private wells may be of insufficient depth to take advantage of contaminant attenuation processes. In most geologic settings deeper wells exhibited lower frequencies and amplitudes of contamination than shallow wells. Total coliform bacteria and nitrate-nitrogen data from this study followed this general trend. At the same time, however, a substantial fraction of wells > 100 feet deep were found to be contaminated (21% contained total coliform bacteria, 32% contained atrazine), suggesting that depth alone does not ensure well protection, and that indiscriminate penetration of potentially protective strata, and failure to reestablish protection through effective grouting, is a likely cause.

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