

AQUIFER VULNERABILITY IN THE PIEDMONT AND COASTAL PLAIN: SOME ENVIRONMENTAL TRACER EVIDENCE OF RECHARGING

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REFERENCE: *Proceedings of the 1997 Georgia Water Resources Conference*, held March 20-22, 1997, at The University of Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Abstract. Detectable tritium, elevated nitrate concentration, and radiocarbon in ground water are used as tracers from the surface environment in surveys to determine the innate (i.e., physical hydrologic) vulnerability to contamination of major aquifers in different geologic provinces. Aquifers in the piedmont and innermost coastal plain show widespread vulnerability. The more widely and readily obtained nitrate data suggest that higher vulnerability also occurs in several parts of the middle and lower coastal plain. However, natural geologic or hydrologic protection of principal aquifers is evidenced in many coastal-plain areas by very old ground water (determined by ¹⁴C).

INTRODUCTION

The degree of ease by which a major aquifer can become contaminated from the surface environment is a basic characteristic that should be important in planning and subsequent permitting decisions and in management programs (e.g., wellhead protection). Aquifer-protection effort then can be directed toward those areas more in need rather than those inherently more protected. Obtaining such information for representative parts of each aquifer of principal use is not easy. Most traditional methods for such investigation (hydrologic or geologic) are expensive, time consuming, weak in inference, or prone to error when limited results are extrapolated over large areas.

Aquifer vulnerability to contamination is restricted here to those aspects controlled by the prevailing geologic and ground-water hydrologic conditions, both natural and those induced by pumping. Lower innate vulnerability represents some factor, usually stratigraphic, that impedes the descent of potentially contaminated ground water from the surface environment to the aquifer. Here we ignore ameliorative factors, other than to note that most materials in the shallower zones are leached and acidic and are not well suited for reaction or sorption of contaminants.

RATIONALE AND METHODS

Degree of vulnerability is basically equated here to rapidity and proximity of nearest significant recharging. Because

geologic conditions mainly control the vulnerability, these surveys are conducted and summarized by geologic province. Existing production wells are used because vulnerability under the stress of persistent use (pumping) is the most pertinent.

Environmental tracers are those that are naturally emplaced everywhere and include nuclear-weapons contaminant tritium (³H) in rainfall and natural radiocarbon (¹⁴C) in soil-zone CO₂ (which dissolves into infiltrating waters). Here we add another chemical that is commonly of artificial origin: nitrate. While there is a low natural nitrate input to recharge from soil and rainfall, a greatly enhanced tracer signal comes from such common and widespread (though not ubiquitous) sources as fertilizers, septic wastewater, or even soil disturbance. Natural processes in aquifers (assimilation and nitrate reduction) tend to reduce or remove nitrate, thereby erasing the signal at some point beyond the recharge location.

Finding tracers of recent origin in an aquifer essentially "proves" a high degree of vulnerability in the vicinity (though different ages of tracers change the criteria). Not finding a true environmental tracer that is applied everywhere evidences a lower vulnerability. Failing to find a tracer that is common but not applied everywhere (here elevated nitrate) proves nothing in one instance, but its absence or comparative rarity over wide areas gives some evidence for lower vulnerability. Differences in tracer age also imply differences in vulnerability. A limitation at present is uncertainty in nitrate reduction rates and natural input levels. This is accommodated in these regional generalizations by noting the degree of agreement when one uses increasingly high threshold concentrations (increasingly unlikely to be natural or old).

Dissolved-nitrate concentration (or nondetection) has been determined for every principal public-supply well in South Carolina (>1600), scattered private wells, and additionally in home and farm wells in a special wide-area survey in agricultural areas (>800 wells). Interpretations are made from the apparent regional clusterings of results when assessed by county, using as an index the percentage of wells with concentrations at or above a specified concentration. Strength is added if similar interpretations can be made from different concentration thresholds, ranging here from the detection limit to one-half the drinking-water limit. Smaller special surveys

in representative areas of important use analyzed for ^3H or ^{14}C in ground water.

RESULTS AND DISCUSSION

Piedmont

Nuclear-era (post-1954) contaminant tritium is present (i.e., detected at $\geq 8 \pm 8$ TU, "tritium units") in the overwhelming majority of supply wells investigated in the piedmont (58 of 70 wells in 1 major and 2 minor study areas encompassing 59 public-supply and 11 private wells: Stone et al., 1992; 5 of 7 piedmont wells in a Georgia study gave similar results: Rose, 1992). (Note that ^3H was always far below drinking-water limits.) Acute vulnerability of the piedmont fractured crystalline-rock aquifer is also strongly suggested by the hydrologic evidence for a direct interconnection between it and the overlying water-table aquifer in the granular saprolite (Heath, 1984), an interpretation reinforced by the abundance of ground-water contamination sites in this province (Devlin and Bucklin, 1996; Christian et al., 1992).

Despite this evidence, there still exist strongly divergent opinions concerning the overall characteristic status of vulnerability in the Appalachian piedmont. Some invoke a natural clayey "protective barrier" in the overlying saprolite layer (DNR, 1994) while others consider the interpretation of typically high vulnerability in the piedmont to be mainly a "myth", challenged by local indications of artesian or confined conditions (Emery and Crawford, 1994). The multi-state extent and increasingly urban and industrialized nature of this region make correct interpretation important for aquifer protection.

Nitrate is very commonly detected in piedmont well waters ($>80\%$ of wells in most counties in both the rural-well survey (≥ 0.1 mg/l N-NO_3^{-1} [milligrams per liter as N]) and in public-supply wells (≥ 0.02 mg/l). The surface environment is virtually the sole origin for this convenient tracer. At concentrations less-readily attributable to any natural conditions (say, ≥ 1 mg/l) the piedmont still stands out by the very common incidence: in most counties $>70\%$ of wells in the rural survey and $>20\%$ of public-supply wells. Even for 5 mg/l (one-half the drinking-water limit), of the 17 counties exclusively within the piedmont, 12 and 10 respectively have wells above this threshold in the rural and public surveys (10-46% and 2-23% of wells per county). These results suggest a relatively recent artificial origin in numerous cases (coming from the era of artificial fertilizers, septic tanks, etc.). Figures 1 & 2 are examples showing the distinct sorting by geographic area at some selected threshold concentrations.

This line of evidence for recent recharge and vulnerability is conservative because many sites will not have the elevated nitrate tracer present in the surface environment (unlike ^3H) and nitrate can be removed by natural processes (although not as readily in these typically oxygen-rich ground waters). Absence of nitrate, however, does not necessarily indicate a

lack of rapid local recharging. The strength of evidence here lies in the wide-area and abundant sampling for nitrate, which supports the indications from ^3H , the other contaminants, and geologic characteristics. High vulnerability is seen to be widely common in the piedmont region, and is interpreted to be the general condition for the entire region. Specific sites or minor types of exception seem incapable of strongly challenging this overall interpretation.

Inner Coastal Plain

Less debate accompanies the interpretation of high vulnerability for the very innermost part of the coastal plain, the sandhills area. Wells can tap either the sedimentary aquifer or, in places, the shallowly buried extension of the crystalline rock aquifer. The clear majority of wells examined (63 of 86) show nuclear-era ^3H (1 major and 1 minor study area, 85 public-supply wells and 1 private well). Even ^{14}C concentration in dissolved inorganic carbon sometimes directly shows nuclear-era recharge (e.g., Darlington County W&S Authority well 5: 105 ± 2.5 PMC [percent modern carbon] which is compared to a lower pre-nuclear-era value of 100 PMC).

Nitrate detection was predominant in the inner coastal plain also, although slightly less so than in the piedmont (most counties $\geq 60\%$ of wells, in both surveys). The inner coastal plain was similarly marked at higher threshold concentrations (Figs. 1 & 2). At the higher threshold (5 mg/l) within the first row of coastal-plain counties (which also include small amounts of piedmont) 20-31% and 1-13% of wells per county were marked in the rural and public surveys.

Slightly farther seaward, but still within the inner coastal plain, it is common for wells not to show nuclear-era ^3H . Presence of the tracer can be prevented by deeper and horizontally longer flow routes between recharging and the well intakes, or be obscured by mixing and dilution with deeper water in wells with long screens. ^{14}C often still evidences relatively young ground water and relatively high vulnerability for this region (e.g., Shaw AFB well 5: 91.1 ± 2.2 PMC).

Nitrate detections in this area remain high, especially eastward toward the Pee Dee River region and adjacent to the North Carolina border (where the characteristic extends to the coast). The controlling factor is not yet discernable: perhaps shallowing of the major aquifers toward the Cape Fear arch (i.e., geologic control) or abundance of agriculture in the Pee Dee region (tracer distribution).

Middle and Lower Coastal Plain

Still farther toward the coast, the wedge of sediments thickens, aquifers can lie deeper, and overlying strata can be thick, areally extensive, and sometimes of low permeability. Highly effective confinement and hydrologic isolation from the surface environment and the water-table aquifer become possible here, along with low to very low vulnerability (the water-table aquifer is vulnerable everywhere of course). Even

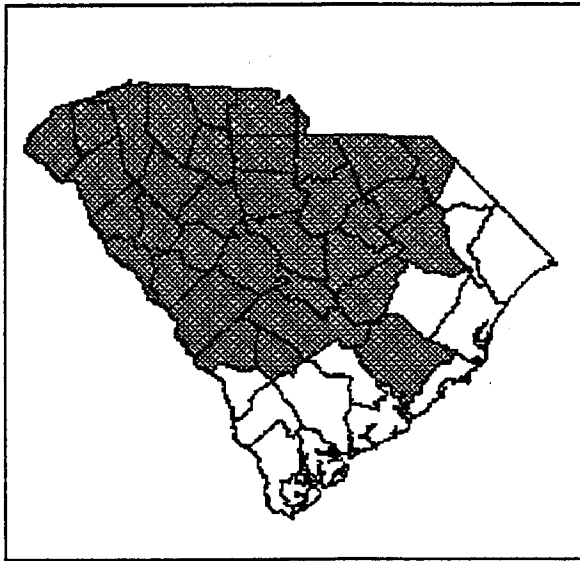


Figure 1. Counties with 20 percent or more of public-supply wells equal to or greater than 0.1 mg/l NO₃-N.

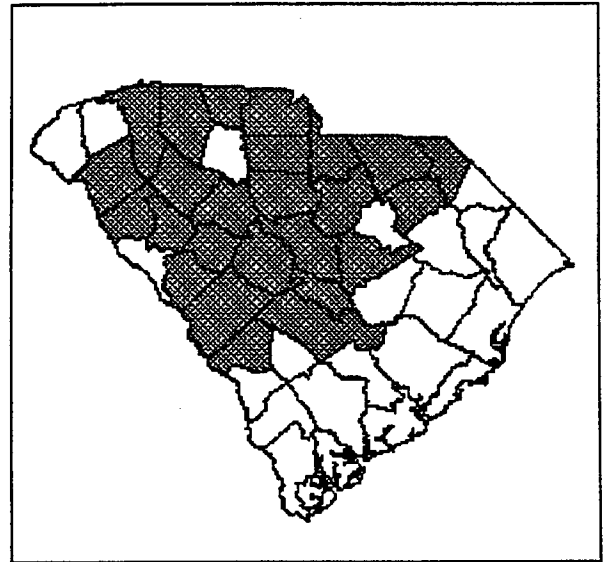


Figure 2. Counties with 20 percent or more of public-supply wells equal to or greater than 1 mg/l NO₃-N.

the *shallowest* major aquifer in many areas evidences this low vulnerability provided by natural geologic protection. The Tertiary limestone aquifer exhibits old ground water and low vulnerability in wide areas (e.g., Lieber Corr. Inst., near Jedburg: 3.9 ± 0.1 PMC or ca. 19,000 years old, here correcting for dilution using the standard $\delta^{13}\text{C}$ method). Nitrate detection shows a sharp transition in the middle coastal-plain counties in the rural survey (to $\leq 20\%$ in many counties) except for somewhat higher values along the coast. Public-supply wells similarly show far less detection in the lower coastal plain in the regional sense, but with several higher-incidence counties (especially Berkeley Co., with 21% of public-supply wells ≥ 0.1 mg/l and 1% ≥ 1 mg/l) (Figs. 1 & 2) plus the North Carolina border region mentioned above. There are greater internal differences within this region and between the two surveys (the latter may possibly relate to deeper wells for public supply or more localized intensive agriculture).

An important finding is that despite the widespread indications of lower (to in places very low) vulnerability in some middle and seaward portions of the coastal plain (shown by ^{14}C and stratigraphy) other extensive areas there are dissimilar and more vulnerable, including some important heavily used portions of aquifers. ^3H shows this for parts of the most shallowly buried (subcrop) area of the Tertiary limestone aquifer (e.g., nearer the Santee River valley at Elloree, 10 & 27 TU; Santee, 21 & 34 TU). ^{14}C similarly shows it but is complicated by intermixture of recharge water into older background ground water of lower ^{14}C content (Elloree gives only 20.5 ± 0.2 PMC, but this is high when compared to *upflow* values at Orangeburg National Fish Hatchery, 8.9 ± 0.2 PMC).

A similar mixing-dilution situation exists at Hilton Head Island on the coast (Landmeyer and Stone, 1995).

CONCLUSIONS

Environmental tracers of several types, each with its own advantages, are beginning to give strong indications of degrees and differences in aquifer vulnerability to contamination on a regional and subregional basis. The piedmont and innermost part of the coastal plain are widely vulnerable in the aquifers typically used, as are several portions of the middle and lower coastal plain (apparently most so where the limestone aquifer is not well confined). Within these areas there is added need for effective remediation of contamination and for protective measures for aquifers and individual wells. To date, this information has been used mainly in two ways: 1) agency permitting decisions for sites in areas of lower vulnerability (e.g., occasional alternative construction or monitoring requirements) and 2) selection of higher-need areas for earliest wellhead-protection delineations. General attention should now shift to how best to involve knowledge of vulnerability in remediation and water-supply decisions. Specific further investigative work should emphasize gaining detail: intracounty, aquifer-specific, and depth-related analyses of the tracer data.

ACKNOWLEDGMENT

Funding was provided by US EPA Region IV under Section 106 and FIFRA.

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