U.S. Department of the Interior—U.S. Geological Survey
National Water-Quality Assessment Program

Predicting Ground-Water Vulnerability to Nitrate in the Puget Sound Basin

by M.L. Erwin and A.J. Tesoriero*

What is ground-water vulnerability?

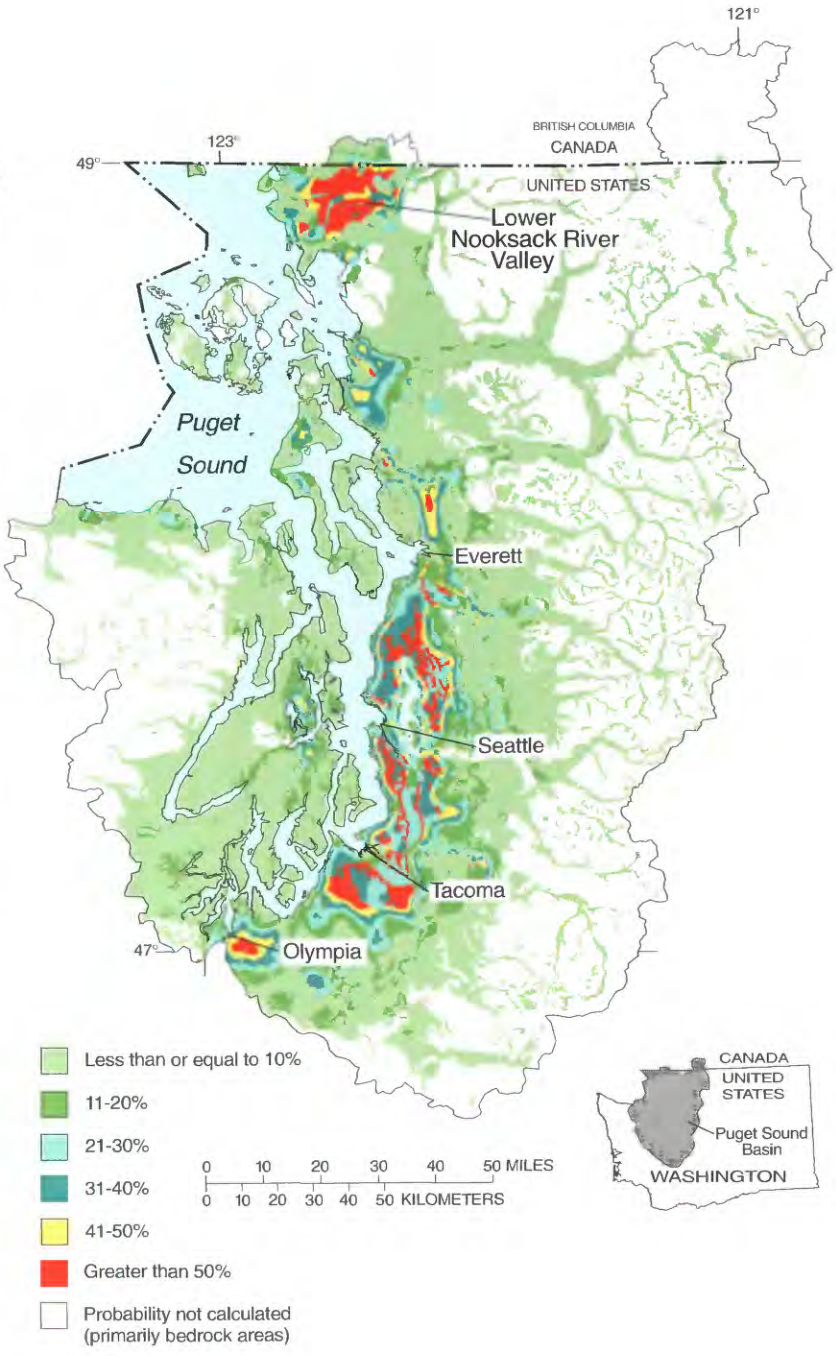
It is an estimate of the relative risk of ground-water contamination by a particular constituent, such as nitrate.

Where is the ground water most vulnerable?

In the Puget Sound Basin, shallow wells in aquifers that have coarse-grained glacial deposits at the surface and a high percentage of urban (residential, commercial, and industrial) and(or) agricultural land use in the vicinity are most vulnerable to nitrate contamination. For example, shallow wells in agricultural areas overlying coarse-grained glacial deposits, like much of the Lower Nooksack Valley, or in urban areas overlying such deposits, like parts of Tacoma and Olympia, have a greater than 50% probability of nitrate concentrations at or above 3 milligrams per liter (areas in red on the vulnerability map to the right). Nitrate concentrations at or above 3 milligrams per liter (mg/L) are well above naturally occurring levels in the Puget Sound Basin (see Brown and Caldwell, 1985, for example), indicating an anthropogenic (human-related) source of nitrate.

Why is vulnerability to nitrate of concern?

- Nitrate contamination has been suggested as an **indicator of overall ground-water quality** (U.S. Environmental Protection Agency, 1996a).
- Because drinking water with high nitrate concentrations is a **potential health risk**, the U. S. Environmental Protection Agency has set a standard for nitrate in drinking water of 10 mg/L (U.S. Environmental Protection Agency, 1996b). Identifying areas in the Puget Sound Basin where ground water has been impacted by anthropogenic activities (nitrate concentrations at or above 3 mg/L) can help water resource managers protect the water supply by targeting land-use planning and monitoring programs to these vulnerable areas.



Vulnerability map. Probability (in percent) of detecting nitrate at concentrations of 3 milligrams per liter or greater in wells that are 50 feet deep in the Puget Sound Basin.

*Author for correspondence: U.S. Geological Survey, 1201 Pacific Ave., Suite 600, Tacoma WA 98402

How was ground-water vulnerability to nitrate predicted?

A vulnerability model was created by relating existing nitrate data to factors describing:

- **aquifer susceptibility**—the ease with which a contaminant can reach the aquifer, determined by natural factors, and
- **contaminant availability**—the availability of sources of nitrate at or near the land surface, determined by anthropogenic factors.

Method

Using logistic regression (see below), the occurrence of elevated nitrate concentrations (at or above 3 mg/L) in samples from 1,967 public supply wells was related to natural factors to assess aquifer susceptibility, and to natural and anthropogenic factors to assess ground-water vulnerability. Data were from the Washington State Department of Health. Significant factors were well depth, surficial geology, and the percentage of agricultural and urban land use within a 2-mile radius of a well.

Assessment of aquifer susceptibility

The probability that a well has an elevated nitrate concentration was related to well depth for each of three types of surficial geology in the basin (graph a).

Assessment of ground-water vulnerability

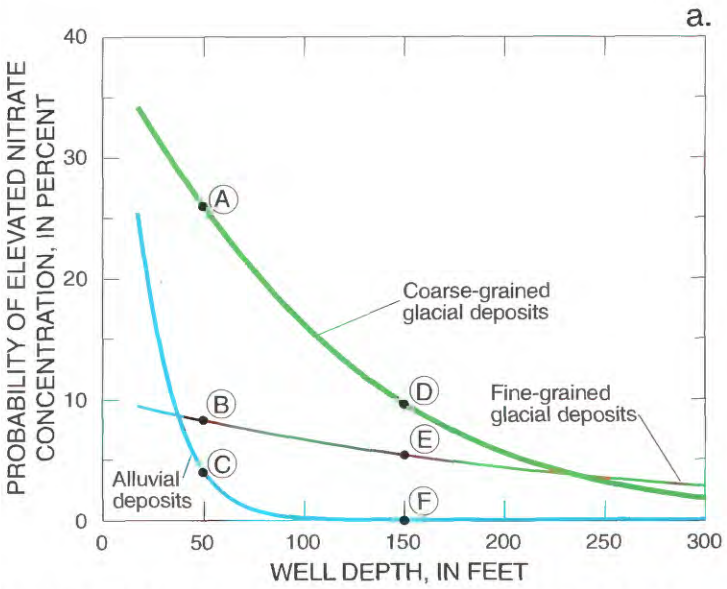
To create the vulnerability model, significant natural factors were combined with significant anthropogenic factors: percent agricultural and percent urban land use within a 2-mile radius of the well (graph b). (Percent land use was calculated for a range of radii surrounding each well and related to the occurrence of elevated nitrate concentrations; a 2-mile radius provided the best fit to the data.)

Creation of a vulnerability map

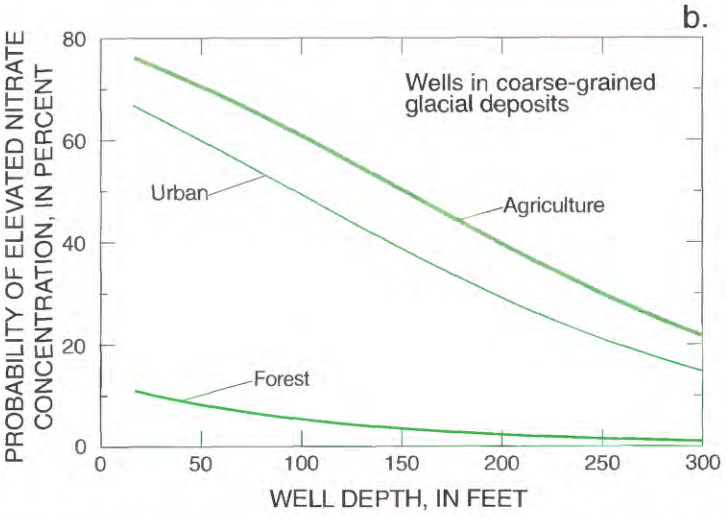
The map on p. 1 was created using the vulnerability model (see the equation below) and geographic information system (GIS) coverages of the surficial geology and land uses in the basin. Maps can be created to depict the probability of elevated nitrate concentrations for wells of any depth.

Evaluation of the vulnerability model

The model was evaluated using existing data for 1,729 mostly domestic wells in the Puget Sound Basin. Data were from the USGS National Water Information System.



Shallow wells with coarse-grained glacial surficial deposits (for example, well A) are most susceptible to elevated nitrate concentrations. (See figure on opposite page for well characteristics.)



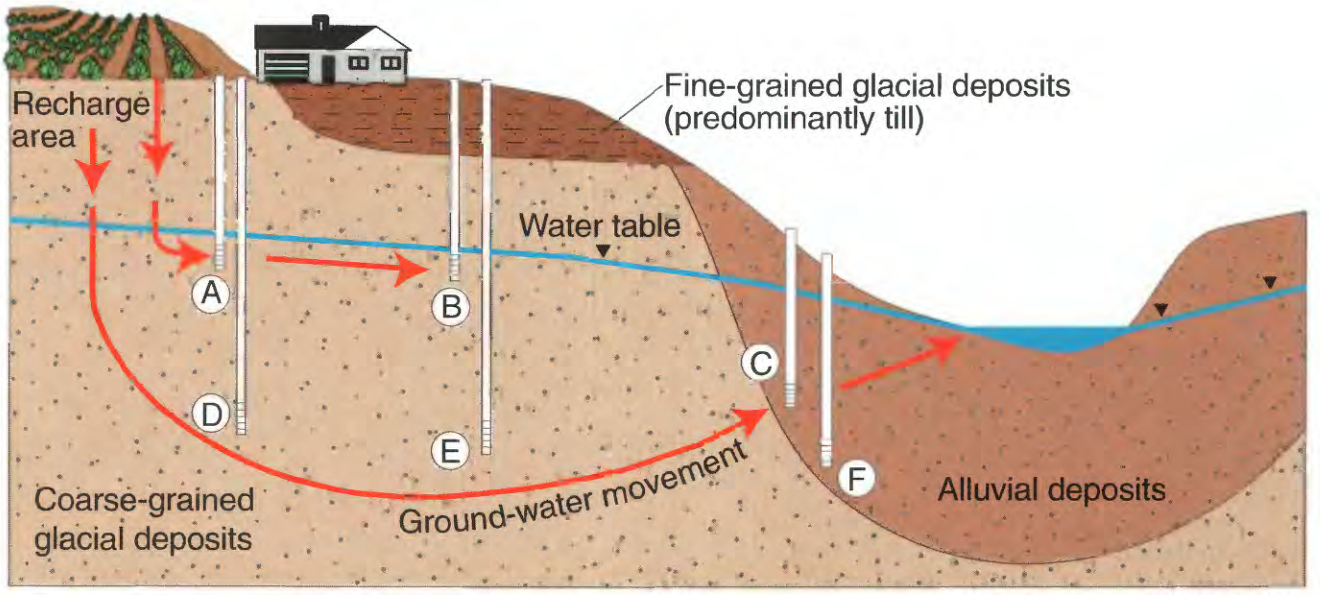
Wells in areas of coarse-grained glacial surficial deposits in intensive agricultural and urban areas are significantly more vulnerable than are wells in forested areas. Probabilities were calculated assuming 100% of the indicated land use within a 2-mile radius of wells; therefore, this graph illustrates the maximum effect of each land use on ground-water vulnerability.

Logistic regression

In the vulnerability model, the probability (P) that a well has a nitrate concentration at or above 3 mg/L is related to natural and contaminant availability factors as follows:

$$P = \frac{e^{(A + B(\text{Well Depth}) + C(\%\ \text{Urban Land Use}) + \ldots.)}}{1 + e^{(A + B(\text{Well Depth}) + C(\%\ \text{Urban Land Use}) + \ldots.)}}$$

The outcome of this equation is a *binary* variable—whether ground water will or will not have 3 mg/L or greater of nitrate. Values for the intercept parameter A and the coefficients B and C are determined using a best-fit method similar to linear regression. Once these values are determined for each surficial geology type, then available data on land use, surficial geology, and well depth can be used to create vulnerability maps.



(NOT TO SCALE)

Ground-water movement and susceptibility in a typical alluvial valley in the Puget Sound Basin. Well *A* has the highest susceptibility to contaminants because it is in an area of coarse-grained glacial surficial deposits where water from the surface (precipitation or irrigation water) moves downward relatively easily (high recharge).
Well *B* is less susceptible because the overlying fine-grained glacial surficial deposits limit recharge.
Of the three shallow wells, well *C* has the lowest susceptibility; it is near a ground-water discharge area (a river) and thus intercepts water that has likely followed a longer flow path.
The deeper wells *D*, *E*, and *F* are less susceptible than the shallow wells in the same environment because it will take longer for a contaminant to reach them. Susceptible areas become vulnerable when contaminant sources are present.

How susceptibility and vulnerability assessments help with water-resource management

Planning land use

Areas where ground water is more susceptible to contamination can be identified. This information can be used in locating land-use activities that are potential sources of contaminants, such as landfills and high-density septic systems. Maps that display the susceptibility of an aquifer system can help educate the public and encourage its support of suitable land-use planning.

Targeting ground-water monitoring

Inspections, data collection, and other monitoring efforts can be targeted to vulnerable areas where land uses that are known sources of contaminants already exist. For example, public water systems are required to sample wells periodically for contaminants. Targeting sampling to those areas identified as more vulnerable to the contaminant of interest would result in more effective and less costly monitoring programs (Ryker and Williamson, 1996; Vowinkel and others, 1996).

Monitoring changes in risk of nitrate contamination of ground water

The probability of elevated nitrate concentrations calculated by the vulnerability model can establish a baseline measure of risk both spatially and with depth. Models based on subsequent nitrate data, which are collected periodically, can be used to evaluate changes in risk over time, which could result from changes in land use or because nitrate has traveled farther along ground-water flow paths.

Evaluating risk from other contaminants

Similar models can be created to predict the probability of detecting pesticides or volatile organic compounds if data exist; these models can then be used to assess susceptibility and vulnerability to these contaminants. However, where data on these contaminants are limited, models based on nitrate data could be useful for estimating relative susceptibility (but not vulnerability) to these other contaminants.

Advantages of this method of predicting ground-water vulnerability

- Vulnerability estimates are based upon statistically significant relations between water-quality data (in this case, elevated nitrate concentrations) and explanatory variables such as surficial geology.
- Unlike methods based on assigning categories of risk ("high" or "low"), this method produces vulnerability estimates which are probabilities; these numbers can be directly compared with estimates from other regions.
- Nitrate data are collected regularly and are widely available from State health departments and the USGS National Water Information System, providing much of the information needed for an inexpensive assessment of changes in water quality over time.

References

Brown and Caldwell, 1985, Clover/Chambers Creek geohydrologic study for Tacoma-Pierce County Health Department [variously paged].

Ryker, S.J., and Williamson, A.K., 1996, Pesticides in public supply wells of Washington State: U. S. Geological Survey Fact Sheet 122-96, 2 p.

U. S. Environmental Protection Agency, 1996a, Environmental indicators of water quality in the United States: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 841-R-96-002, 25 p.

U.S. Environmental Protection Agency, 1996b, Drinking water regulations and health advisories: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 822-B-96-002, 11 p.

Vowinkel, E.F., Clawges, R.M., Buxton, D.E., Stedfast, D.A., and Louis, J.B., 1996, Vulnerability of public drinking water supplies in New Jersey to pesticides: U. S. Geological Survey Fact Sheet 165-96, 4 p.

This fact sheet is based on the journal article

Tesoriero, A.J., and Voss, F.D., in press, Predicting the probability of elevated nitrate concentrations in the Puget Sound Basin—Implications for aquifer susceptibility and vulnerability, Ground Water, about 8 p.

Fact Sheet 061-97 by M.L. Erwin and A.J. Tesoriero
GIS by F.D Voss; Illustrations by E.L. Inkpen and C.J. Dean

For more information on the Puget Sound NAWQA, contact:
Project Chief
U.S. Geological Survey
1201 Pacific Avenue, Suite 600
Tacoma, WA 98402
Phone: (253) 593-6510 Email: nawqa_puget_wa@usgs.gov

Visit the Puget Sound NAWQA home page: http://wwwdwatcm.wr.usgs.gov/ps.nawqa.html

National Water-Quality Assessment (NAWQA)

One of the greatest challenges faced by scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. The U. S. Geological Survey NAWQA program is the first nationwide evaluation of the historical, current, and future condition of these resources. This ground-water vulnerability model was designed by NAWQA scientists in the Puget Sound Basin, which is one of 60 major river basins and aquifers in the U.S. that are included in the program.