DRAFT!

For Personal Use Only.

Assessing Vulnerability of Groundwater

May 2001

This booklet is part of a series of educational brochures and slide sets that focuses on various aspects of water source protection. The series has been prepared jointly by the University of California Agricultural Extension Service and the California Department of Health Services.

For further information about this and other documents in the series, contact the project team leader (see below) or visit the following website:

www.dhs.ca.gov/ps/ddwem/dwsap/DWSAPindex.htm

Authors: **Thomas Harter**, Department of Land, Air, and Water Resources, University of California at Davis, and **Leah G. Walker**, California Department of Health Services, Santa Rosa, Calif.

Editor: Larry Rollins, Davis, Calif.

Layout crew: Larry Rollins and Pat Suyama

Photo credits:

- U.S. Natural Resources Conservation Service (cover)

Cover photo: Crop duster spraying pesticide. Vulnerability is a measure of the risk that such an activity might affect groundwater quality.

Project Team leader: Thomas Harter, Department of Land, Air, and Water Resources, University of California at Davis

Funding Agency: California Department of Health Services

This booklet introduces the topic of vulnerability assessment and mapping. Although it discusses groundwater vulnerability exclusively, the approaches for surface water and watershed vulnerability assessments are, in principle, very similar to the approach used for groundwater assessments. Hence, much of the presentation here applies to watershed vulnerability as well.

The booklet consists of three sections. The first section provides a general overview, to answer the following frequently-asked questions:

- What is vulnerability, and how does it relate to similar terms, such as susceptibility, pollution risk, and contamination risk?
- Vulnerability of *what* groundwater?
- Vulnerability *to what*?
- Why assess vulnerability?
- Which factors determine the degree of vulnerability?
- How do we characterize vulnerability?
- What is an appropriate scale of investigation for a vulnerability assessment?
- How are uncertainties taken into account when mapping vulnerability?
- What are the limitations of vulnerability assessments?
- What is the role of a vulnerability assessment in groundwater management?

The second section provides a summary of the vulnerability analysis method recommended by California's Drinking Water Source Assessment and Protection (DWSAP) program, administered by the California Department of Health Services (DHS). It also describes other commonly-used vulnerability assessment methods and provides examples.

The closing section contains a short guide describing how to select a vulnerability assessment method and how to verify and audit the results.

Overview

What is Groundwater Vulnerability?

Groundwater vulnerability is a measure of how easy or how hard it is for pollution or contamination at the land surface to reach a production aquifer. Stated another way, it is a measure of the "degree of insulation" that natural and manmade factors provide to keep pollution away from groundwater. Vulnerability is high if natural factors provide little protection to shield groundwater from contaminating activities at the land surface. Vulnerability is low, on the other hand, if natural factors provide relatively good protection and if there is little likelihood that contaminating activities will result in groundwater degradation. The term first was used in Europe, in the 1960s. The following offers a number of definitions, from various sources, in chronological order.

- "Aquifer vulnerability is the possibility of percolation and diffusion of contaminants from the ground surface into natural water-table reservoirs, under natural conditions." (Margat, 1970, quoted in Vrba & Zoporozec)
- "Vulnerability is the degree of endangerment, determined by natural conditions and independent of present source of pollution." (Olmer and Rezac, 1974, quoted in Vrba & Zoporozec)
- "Vulnerability is the risk of chemical substances — used or disposed of on or near the ground surface—to influence groundwater quality." (Villumsen et al., 1983, quoted in Vrba & Zoporozec)
- "Groundwater vulnerability is the sensitivity of groundwater quality to anthropogenic activities which may prove detrimental to the present and/ or intended usage-value of the resource." (Bachmat and Collin, 1987, quoted in Vrba & Zoporozec).
- "[Vulnerability of a hydrogeological system is] the ability of this system to cope with external, natural and anthopogenic impacts that affect its state and character in time and space." (Sotornikova and Vrba, 1987, quoted in Vrba and Zoporozec)
- "[Groundwater vulnerability is] a measure of the risk placed upon the groundwater by human activities and the presence of contaminants [...]. Without the presence of contaminants, even the most susceptible groundwater is not at risk, and thus, is not vulnerable." (Palmquist, 1991, quoted in Vrba & Zoporozec)
- "[Groundwater vulnerability is] the tendency of, or likelihood for, contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer." (U.S. National Research Council, 1993, quoted in Vrba & Zoporozec)
- "Vulnerability is an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts." (International Association of Hydrogeologists, Vrba & Zoporozec, 1994)
- "Vulnerability is a combination of (a) the

inaccessibility of the saturated zone, in a hydraulic sense, to the penetration of pollutants; and (b) the attenuation capacity of the strata overlying the saturated zone as a result of physicochemical retention or reaction of pollutants. [...] It is [...] a statement about the intrinsic characteristics of the strata (unsaturated zone or confining beds) separating the saturated aquifer from the land surface, thus providing an indication of the impact of land-use decisions at that point on the immediately underlying groundwater." (Foster, 1998; *in*: Robins (ed.), 1998)

In describing and defining groundwater vulnerability, a number of issues must be examined and clarified, all of which refer to these two questions: vulnerability *of what?*, and vulnerability *to what?*

As a starting point, we must realize that any groundwater is, in principle, vulnerable to human activity: no groundwater is completely isolated from the above-ground environment. And practically all groundwater originates as recharge at the land surface, proving that there is a direct link between the surface and groundwater. (Some groundwater is indeed of magmatic origin and formed within the subsurface.) The degree of vulnerability will depend on environmental conditions, on how we define groundwater and the part of groundwater we are interested in (hence, the question, "vulnerability *of what?*"), and on the time-scale of interest. It also depends on whether or not a vulnerability measure also is intended to account for the presence and type of pollutants (hence, "vulnerability *to what?*").

Groundwater is a fairly ubiquitous resource. When defining vulnerability, we therefore need to ask what part of groundwater is to be assessed. For example, are we to consider only groundwater at the water table? Or should we instead assess all groundwater within the production zone? Should we also consider groundwater in deeper production aquifers? Should we use a simpler "black box" approach and consider groundwater only at the production or domestic well, where it is actually used?

Because the shallowest groundwater zone is typically the most vulnerable, vulnerability assessments are mostly concerned with the vulnerability of the uppermost aquifer (in a multi-aquifer system) or with the water table (in an unconfined-aquifer system).

Some methods of assessing vulnerability also account—directly or indirectly—for the travel time between the water table and a well, by considering aquifer permeability or travel-time zones. Examples are U.S. EPA's DRASTIC method by Aller et al., 1987, California DPR's groundwater vulnerability assessment method, and DHS's vulnerability analysis method.

Time scales are important in defining vulnerability. The practical question is: should we consider groundwater vulnerable to today's activities if the recharge time is tens, hundreds, thousands, or tens of thousands of years? Many geothermal water resources—geysers, hot springs, and geothermal wells, for example—deliver groundwater whose recharge period is measured in millenia. Certainly, the vulnerability question has been raised for such resources, since they are important as natural history markers, as tourist attractions, as sources of drinking water with particular health benefits, or as an energy resource.

Consideration of the time element is an important part of defining a vulnerability assessment.Typically, if a pollutant will take a very long time to reach groundwater (because, for example, groundwater exists at great depth) or if the pollutant travels relatively slowly within the aquifer (because of low hydraulic conductivity, or because of low groundwater velocities), then groundwater vulnerability is thought of as being low. If, on the other hand, recharge reaches the water table within a relatively short time because the aquifer is shallow or because geologic materials above the aquifer are highly permeable, then vulnerability is considered to be high. Deep groundwater is considered less vulnerable than shallow groundwater, because of the longer travel times necessary for a pollutant to reach a well.

Time scales are also important when mapping vulnerability to specific pollutants that become less harmful over time. For example, vulnerability to pathogen contamination is only a concern where travel times to groundwater (or to groundwater wells) is less than a few months to a couple of years. Also, many organic chemicals degrade over long time periods, becoming less harmful substances. (For some pesticides, this time period may be on the order of weeks to months.)

Vulnerability may or may not include an assessment of whether pollutants are present or absent in the region of interest. Vulnerability that is independent of whether or not contaminants (pollutants) are present and which focuses primarily on a description of natural environmental conditions is often (though not always) referred to as "susceptibility", "natural vulnerability", "aquifer sensitivity", or "intrinsic vulnerability".

Vulnerability is also a function of pollutant type. Different pollutants (or contaminants) behave differently, depending on their chemical or microbiological make-up. Pollution-type-dependent vulnerability, or vulnerability to specific land uses, is sometimes referred to as "specific vulnerability" or "integrated vulnerability".

Why Assess Groundwater Vulnerability?

The purpose of vulnerability assessments is not to create scientific insight, but to provide a decision-making tool based on the best available data and good scientific judgement. In undertaking a vulnerability assessment, this perspective and the breadth of definitions should be discussed and defined early in the process. In doing so, it is important to understand that vulnerability serves more of an economic goal than a scientific analysis of groundwater resources.

Vulnerability assessments serve primarily to direct groundwater protection efforts such that the most environmental and public health benefits are achieved at least cost. The Natural Research Council (1993) identified four general objectives typically achieved by groundwater vulnerability assessments: (1) to facilitate policy analysis and development at the local and regional level; (2) to provide program management; (3) to inform land use decisions; and (4) to provide general education and awareness of a region's hydrogeologic resources. In California and other states, vulnerability assessments can be used to obtain waivers for specific groundwater monitoring requirements. They are also used to define areas with special regulations for agro-chemical applications.

The usefulness of vulnerability maps can be argued, as there are a number of pros and cons to vulnerability assessments. Against the use of vulnerability maps for land use planning, one can argue that groundwater flow conditions and the transport properties of the subsurface are so complex that they cannot be appropriately captured by any vulnerability tool. A second group of arguments against vulnerability zoning arises from the fact that all groundwater is vulnerable to land pollution and that the only geographically-differing factor is the time-scale for the pollution to reach groundwater. On the other hand, land use decisions will have to be made, land management practices need to be sensitive to the risk for groundwater contamination, and not all anthropogenic activities can be carried out in isolation of groundwater. Time scales and distinctions based on travel time are important, at least with respect to some pollutants. Time scales are also important in placing groundwater monitoring wells and in scheduling and providing for planning and action-response time in case pollution does occur. So a need exists to provide at least some general guidance to land use planners, decision makers, and water users that allows them to make decisions that are economically sensible while at the same time geologically reasonable.

What Factors Determine Vulnerability?

The thickness and hydraulic properties of the geologic formations above the aquifer—the unsaturated zone and confining layers above the aquifer—are the key factors determining the vulnerability of an aquifer system. They are the principal natural controls determining the recharge rate and recharge time to the aquifer. The unsaturated zone also provides key groundwater protection by:

- intercepting, sorbing, and eliminating pathogenic viruses and bacteria
- sorbing and degrading many synthetic organic chemicals
- attenuating heavy metals and other inorganic chemicals through sorption and complexation with mineral surfaces within the unsaturated zone and through uptake into plants and crops (e.g., fertilizer)

Much of the degradation of synthetic chemicals (e.g., pesticides, solvents) occurs in the soil layer, the uppermost part of the unsaturated zone. The soil layer, typically from 2 to 6 feet thick, is a very active zone microbiologically. The relatively high microbial activity, higher organic matter content, and the presence of roots provide more degradation and removal capacity in the soil than in the underlying unsaturated zone. The potential of the soil and the unsaturated zone to sorb, degrade, or eliminate substances depends on the type of pollutant and therefore is considered only in vulnerability studies that are specific to certain land uses (also referred to as "possible contaminating activities").

Unsaturated zone flow and transport processes are generally complex and difficult to measure, in part because of the large amount of natural variability found in soils, sediments, and rocks. Hence, mappable soil properties (e.g., infiltration capacity, permeability, soil type) allow the analyst only to approximate actual transport processes.

The amount of recharge occurring at the land surface is another important factor that determines vulnerability. If climatic conditions are such that little or no recharge occurs at the land surface, downward movement of moisture through the unsaturated zone will be very limited, regardless of the hydraulic properties of the unsaturated zone. Many low-lying areas in central and southern California have effective natural recharge rates that are less than one quarter of one foot per year after accounting for the water uptake by the vegetation growing through the wet winter and spring months. Many of these areas are also farmed intensively, by use of irrigation. At irrigation efficiencies ranging from 50% to 85%, the recharge leaving the bottom of the root zone (after crops have taken their share of water) and recharging through the unsaturated zone to the water table is typically much higher—as much as two feet per year—than under natural climatic conditions.

On irrigated lands where significant precipitation occurs, the amount of recharge to groundwater will depend on a number of factors that are themselves interdependent. Such factors include: the hydraulic properties of the unsaturated zone, the slope of the land surface, and the water uptake through plants and crops. The steeper the slope, the more likely water is to run off into creeks and streams, especially if the soil has a low permeability and resulting low infiltration capacity. On the other hand, water will have little opportunity to run off from a highly permeable soil (e.g., sand), regardless of the slope at the land surface. Once water penetrates into the soil, some or all of it will be taken up by roots for plant transpiration. Within a slope, water may also travel downslope in the shallow subsurface, only to emerge as runoff near the bottom of the slope, recharging a stream. What water is left over below the root zone, after passing through this "sorting" process at and near the land surface, is referred to as "net recharge". It is available to percolate through the unsaturated zone to the water table. The higher the net recharge, the higher the vulnerability of the aquifer.

How Do We Characterize Vulnerability?

A vulnerability assessment is a process by which information relevant to characterizing groundwater vulnerability—however defined—is assembled to produce a map that distinguishes areas of greater groundwater vulnerability from areas of lesser groundwater vulnerability. Vulnerability assessment and vulnerability mapping are sometimes used interchangeably. Numerous schemes have been developed for assessing and mapping vulnerability. These methods can be grouped into three major categories:

- index-and-overlay methods
- process-based computer simulations
- statistical analyses

Index-and-overlay methods are methods based on assembling information on the most relevant factors affecting aquifer vulnerability (soil type, geologic formation type, recharge, etc.), which then is interpreted by scoring, integrating, or classifying the information to produce an index, rank, or class of "vulnerability". The scoring, ranking, and integration methods are based on expert opinion rather than processes and are inherently subjective to some degree. In the United States, the most prominent vulnerability assessment method in this category is "DRASTIC." The vulnerability analysis specified by California's DWSAP program also falls within this category.

The advantage of these methods is that they provide relatively simple algorithms or decision trees to integrate a large amount of spatial information into maps of simple vulnerability classes or indeces. These types of methods are designed to rely on data that are readily available from local, state, or federal government agencies, such as information on soils, water level depth, precipitation, geology, etc. These methods are particularly suitable for use with computerized geographic information systems (GIS), which is a digital form of map making, since they usually involve the overlaying and aggregation of multiple maps showing soil properties, depth to water table, recharge, etc.

Process-based computer simulations afford a great amount of realistic complexity and detail to be built into the vulnerability assessment. Computer models can account for complex physical and chemical processes and at a very detailed scale. Unlike the two-dimensional maps and map layers utilized with other methods, computer modeling allows for a three-dimensional resolution. Geologic and hydrogeologic variations with depth can, therefore, be reproduced to evaluate their effect on vulnerability. Process-based computer models focus on recreating the flow and transport patterns within the unsaturated zone or in an actual aquifer and can be used to compute travel times or concentrations of a contaminant in the unsaturated zone or the aquifer. Computer models do not directly compute vulnerability. Rather, vulnerability is defined as a function of what the computer models simulate. For example, high vulnerability may be defined as any region in the aquifer for which the computer model shows a travel time of less than 5 years. Examples of unsaturated zone models are PRZM, LEACH, and HYDRUS. A popular groundwater computer model is MODFLOW.

The most advanced computer models also allow the analyst to compute the uncertainty that is inevitably associated with the computer model predictions due to shortcomings in the database fed into the computer and due to our limited knowledge of what the "underground world" actually looks like.

Computer models are not commonly used for vulnerability assessment due to their considerable data requirements and the expertise required to implement them. In other words, computer simulation models are rarely an economic alternative for vulnerability mapping. However, computer modeling is an excellent and economic tool of vulnerability mapping if:

- a more localized analysis of specific vulnerability to particular land uses (particular contaminants) is required and sufficient data are available or can be collected to prepare the computer model
- a number of "what-if" scenarios involving complex processes need to be evaluated for making important land use planning decisions

Statistical methods are used to quantify the risk of groundwater pollution by determining the statistical dependence or relationship between observed contamination, observed environmental conditions that may or may not characterize vulnerability (e.g., unsaturated zone properties, recharge), and observed land uses that are potential sources of contamination (e.g., fertilizer applications, septic tank occurrence). Once a model of this dependence or relationship has been developed with the statistical analysis, it can be used to predict—in a similar area elsewhere—the chance or risk of contamination. Such an application requires, of course, knowledge of significant environmental conditions for that area. When statistical methods are used, the risk of contamination is essentially a quantitative measure of "vulnerability". The higher the contamination risk, the higher the vulnerability.

In principle, statistical methods are not much different from index-and-overlay methods: both establish a relationship between inherent natural conditions and groundwater vulnerability (which the statisticians refer to as groundwater contamination risk). In the overlay methods, the relationship is established by a team of experts. In the statistical methods, the relationship is established by statistical analysis. The advantage of the statistical method is that the statistical significance can be explicitly calculated. That provides a measure of uncertainty or certainty of the model. The disadvantage is that statistical methods are difficult to develop and, once established, can only be applied to regions that have similar environmental conditions to the region for which the statistical model was developed.

Few statistical methods exist, and all have been applied to specific regions. In California, the Department of Pesticide Regulations uses a statistical vulnerability assessment that was developed from a statistical analysis of pesticide occurrence in San Joaquin Valley groundwater. The vulnerability assessment is used to delineate and discern areas that are particularly vulnerable to pesticide contamination (called "groundwater protection zones"). Within those areas, certain management practices must be followed when pesticides are applied, to reduce the risk for pesticide leaching.

What Is an Appropriate Scale of Investigation for a Vulnerability Assessment?

Vulnerability maps are typically done at a sub-basin, basin, or regional scale. They are not normally used for site-specific assessments involving areas smaller than a few tens of square miles. The broad generalized categories of parameters used to determine vulnerability provide only broad distinctions of vulnerability. Vulnerability maps are therefore best used to demonstrate large scale, regional differences in groundwater vulnerability.

Vulnerability mapping of an area or region must be distinguished from determining the vulnerability of a specific location, e.g., an individual well or well field, which is but one point on a larger map. Vulnerability assessment of a well location does not involve any mapping, only the computation of a vulnerability index or vulnerability ranking for that particular location (e.g., DWSAP vulnerability analysis).

How Are Uncertainties Taken Into Account When Mapping Vulnerability?

Only statistical methods allow us to quantify (albeit roughly) the degree of uncertainty associated with a vulnerability ranking. Index-and-overlay methods, which rely on qualitative interpretation of broadly-described natural conditions, do not include any measures of uncertainty. The scoring or ranking used in these methods is generally designed to err on the conservative side, that is, it tends to overestimate rather than underestimate groundwater vulnerability.

What Are the Limitations of Vulnerability Assessments?

Vulnerability assessments are a general planning and decision making tool. They should not be mistaken for a scientifically precise prediction of future contamination. Rather, they are a general assessment of the risk that contamination may occur in groundwater. As with any risk analysis, there is no guarantee that the contamination does or doesn't occur.

Because of the implied imprecise nature of vulnerability assessments and the inevitable subjectiveness of the underlying interpretive scheme, the National Research Council (NRC) issued "three rules of groundwater vulnerability". These rules, or limitations, should be spelled out explicitly with every vulnerability assessment:

- All groundwater is to some degree vulnerable
- Uncertainty is inherent in all vulnerability assessments
- There is a risk that the obvious may be obscured and the subtle may become indistinguishable

The latter refers to the danger, especially when using complex vulnerability assessment tools, that in light of the final vulnerability index or ranking one may lose sight of the data used for the analysis and of the assumptions underlying vulnerability assessment schemes.

Vulnerability Assessment Methods and Examples

In the previous section, we distinguished three major groups of vulnerability assessment and mapping methods: index-and-overlay methods, process modeling methods, and statistical methods. In this section we provide a brief overview of a few specific methods. We also provide several examples.

Index-And-Overlay Methods

DWSAP Vulnerability Analysis

The DWSAP Vulnerability Analysis has been developed specifically for determining the vulnerability of drinking water sources in California. That includes both groundwater and surface water sources. An example of an index method, the DWSAP method is based on checklists and a point system derived from generalized hydrologic and hydrogeologic principle. It also relies on expert knowledge, including knowledge of contamination sources and knowledge of travel time. It is a "specific vulnerability" assessment method, as opposed to an "intrinsic vulnerability" or "susceptibility" assessment (see previous section). That's because it explicitly accounts for the presence and type of possible contaminating activities (PCAs) at the land surface and for the known presence of specific contaminants, regardless of a known contamination source.

The DWSAP method defines vulnerability as "a determination of the most significant threats to the quality of the water supply that takes into account the physical barrier effectiveness of the drinking water source." It further states that "the vulnerability determination also considers the type and proximity to the water supply of activities that could release contaminants."

The DWSAP method prescribes a three-part procedure: (1) determination of the PCAs within the source area of a well or surface water intake (a complete list of possible PCAs is provided in the DWSAP documentation); (2) determination of the relative likelihood that contaminants can travel from a potential PCA location to the well or surface water intake (DWSAP calls this the "Physical Barrier Effectiveness" or PBE); and (3) determination of the travel time from various PCAs to the well or surface water intake.

The focus on individual water sources (wells, well fields, water intakes) distinguishes this method from overlay methods such as the popular DRASTIC method or the British GOD method. The viewpoint of the DWSAP method (and of other methods focusing on wellhead protection zones, e.g., that used by the Texas Natural Resource Conservation Commission, Blodgett, 1993) is from the drinking water source (well, intake) backward to the source of the water coming to that well or intake. This viewpoint assesses vulnerability not only as a function of the unsaturated zone overlying the aquifer at the location of the well, but as a function of the soil and unsaturated zone in the entire source area, the aquifer type, and the travel time to the well from individual areas of potential contamination. The product of a DWSAP analysis is a ranked list of all PCAs within the ten-year travel time limits of the source area of a drinking water well. Unlike other vulnerability mapping methods, the DWSAP analysis does not assign a single, specific vulnerability index to particular well or well-field of concern or to a location on a map.

To create a ranked list of all PCAs within the source area (wellhead protection area), each PCA obtains a score for:

- the contamination risk associated with the PCA (1 for low, 3 for medium, 5 for high, 7 for very high),
- the aquifer horizontal travel time from the water table underneath the PCA to the well (5 if less than 2 years, 3 if less than 5 years, 1 if less than 10 years),
- and the physical barrier effectiveness (PBE) with which soils and aquifer can prevent contamination from reaching the well (5 for low, 3 for medium, or 1 for high).

The contamination risk ranking of a PCA is predefined or can be modified through the use of a defined checklist. The travel time is determined by the location of the PCA on a map showing the source area (wellhead) protection zones delineating zones A, B5, and B10 (which correspond to areas of less than 2, 5, and 10 year travel time, respectively). Note, that the aquifer travel time does *not* include the vertical travel time through the unsaturated zone. The latter is indirectly accounted for in the Physical Barrier Effectiveness. The PBE is determined through the use of a checklist, where points are given depending on aquifer type (confined, unconfined, fractured), aquifer materials, depth to water, screened well depth, and well construction. Points for each item are added. The total score determines whether the PBE is low, moderate, or high. The intent of the PBE analysis is to highlight sources that have low or high PBE. By intent, most sources will have moderate PBE.

To obtain the final score, the three scores (contamination risk, travel time, PBE) are added separately for each PCA within each of the three protection zones (A, B5, B10). The PCA scores are listed—in order, from highest to lowest—for each PCA that exists within each travel time zone. The ranked list of PCA scores is the final result of the vulnerability analysis. A well is considered *vulnerable* to those PCAs that score 8 points or more.

The DWSAP vulnerability analysis itself does not produce a vulnerability map. However, by assembling the vulnerability information developed for many wells within a region, a number of maps could be produced: maps representing intrinsic vulnerability (from the PBE scores), maps showing whether a well is vulnerable at all (PCAs with scores of 8 or higher within the 10-year travel time zone), and specific vulnerability maps of individual PCA types. Such maps can then be used by local land use planners and decision makers for zoning decisions, etc. Note that PCAs outside the 10-year travel zone are not considered in the determination of well water vulnerability.

As with other index-and-overlay methods, the check list items (e.g., for determining the PBE) and final PCA vulnerability scoring are based on simple, broad categories. For example, only three types of aquifer are distinguished: confined, unconfined, and fractured rock aquifer. For unconfined aquifers, three types of aquifer materials are recognized: unconsolidated sediments with a significant clay layer above the water table, unconsolidated sediments without a clay layer, and fractured rock. Depth to the water table is categorized into four groups: less than 20 ft., 20–50 feet, 50–100 ft, and greater than 100 ft. The reason for the simplicity of the classifications is two-fold: First, the information required to answer the check list questions must be relatively easy to obtain. And second, the assignment of scores to individual items such as aquifer type and depth to water is not a precise science.

In fact, it is a bit like trying to compare apples with oranges. For example, as part of the score for PBE, the same score is assigned for aquifer material consisting of unconsolidated sediments without a protective clay layer as is assigned for water table depth being more than 100 ft. Both receive 10 points for their effectiveness as a protective barrier. Ten points are also given for a sanitary seal that exceeds 50 feet depth. Ten extra points are given if the unconsolidated sediment has a natural protective clay layer above the water table (20 points total). The same "effectiveness" score of 20 is assigned to the following combinations of unconfined aquifer type, water table depth, and well construction:

- Unconsolidated sediments with clay layer (20 pts.), water level depth 0–20 ft (0 pts), no sanitary seal (0 pts)
- Unconsolidated sediment without clay layer (10 pts), water level depth greater than 100 ft (10 pts), no sanitary seal (0 pts)
- Unconsolidated sediment without clay layer (10 pts), water level depth 0–20 ft (0 pts), sanitary seal 50 ft or thicker (10 pts)
- Fractured rock aquifer (0 pts), water level depth greater than 100 ft (10 pts), sanitary seal 50 ft or thicker (10 pts)

But are any of these combinations really equivalent in their barrier effectiveness? How would we know? One measure would be to model and compare the transport and fate of contaminants in either one of those scenarios. The outcome most likely would be different for each scenario. More importantly, even if we investigated or modeled the contaminant transport at ten different sites that all fell within the same classification above, results would greatly differ between sites.

The aforementioned example illustrates the reason for keeping the check list and scoring simple: because of the uncertainty and imprecision of the scoring system, it is of little additional value to distinguish between more than a couple of different classes for each check list or scoring item. Even the final DWSAP vulnerability list of PCAs should be interpreted carefully and *not too much weight should be given to differences between individual scores.* But the analysis is useful to provide a list of those PCAs that should be of high concern (PCAs scoring above the cutoff) and those that are not a major concern (PCAs scoring below the cutoff). The list is helpful in prioritizing planning and protection efforts, and in providing guidance for additional detailed vulnerability analysis, e.g., with groundwater models, where ambiguity exists.

DRASTIC Vulnerability Mapping (Aller et al., 1987)

DRASTIC is perhaps the most popular vulnerability mapping tool in the United States. Put together by a group of experts and the EPA in the mid-1980s, it has been applied to a number of groundwater basins, regions, even states, including some regions in California.

The name stands for <u>D</u>epth to groundwater, <u>R</u>echarge rate, <u>A</u>quifer media, <u>S</u>oil media, <u>T</u>opography, <u>I</u>mpact of vadose zone media, and hydraulic <u>C</u>onductivity of the aquifer. Similar to Physical Barrier Effectiveness computation in the DWSAP vulnerability analysis, each of these seven parameters are assigned a score. In DRASTIC, scores of 0 to 10 are assigned to each parameter, with 0 meaning low risk for groundwater contamination, 10 meaning high risk for contamination. (By contrast, high PBE scores in DWSAP's method mean low risk for contamination and high barrier effectiveness.) Each parameter is weighted. That is, the scores are multiplied with a parameter-specific weight. The weighted scores of all seven parameters are then added for the final DRASTIC score. Two sets of weights can be used: one for general (intrinsic) vulnerability analysis, one for specific vulnerability to pesticides.

In DRASTIC, the scores are computed for every location within a larger region and mapped. (The same algorithm could be applied to individual wells, which are points on the map.) For the mapping, seven individual maps are prepared, one for each of the seven parameters. The seven maps are then overlayed, and at each point of the map, the final DRASTIC vulnerability score is obtained by computing the score from the seven parameters valid at that location of the map. A GIS system makes this task extremely simple; it would be very cumbersome to implement manually, without the GIS system.

Unlike in the DWSAP analysis, DRASTIC does not account directly for contaminating activities or groundwater contamination already present in the area of interest. It also does not account for the travel time within the aquifer.

DRASTIC scores, like the DWSAP's PBE scores, are meant as a rough measure of the likelihood or risk that groundwater contamination can (or cannot) occur. The advantages and pitfalls are similar to those of the DWSAP PBE scoring. DRASTIC has been critized specifically for underestimating the vulnerability of fractured rocks, when compared to unconsolidated aquifers.

GOD (Foster, in Robins, 1998)

GOD is a vulnerability assessment method developed in Great Britain, where most groundwater resources are in hardrock aquifers, primarily sandstone and limestone aquifers. Unconsolidated overburden or soil layers cover the fractured hardrock in many places. Like DRASTIC, GOD is an index-and-overlay method designed to map groundwater vulnerability over large regions based on a few important parameters; GOD stands for Groundwater occurrence, Overall lithology of the unsaturated zone or overlying aquitard, and Depth to groundwater table. Scores are assigned to each of the three categories and then multiplied to yield a final score. In developing GOD, the method's authors have given particular consideration to the likelihood of fractures or fracture systems to develop in the soils, overburden, or overlying geologic units of the aquifer.

Process-Based Computer Modeling

Process-based computer models imitate the actual physics and chemistry of the contaminant transport in the subsurface, to make predictions about the amount of degradation, sorption, or remobilization that a contaminant may experience as it travels through the subsurface. Computer models can be used to compute the travel time and the extent of contaminant plumes in the subsurface. Such computations are based not on generalized expert or statistical knowledge, but on the fundamental scientific principles controlling the movement of water and contaminants in the subsurface.

Computer modeling codes for unsaturated zone and groundwater modeling abound, often serving very specific applications. Four computer model codes are particularly popular for computing the fate and transport of contaminants as those contaminants travel downward through the unsaturated zone to the water table: VLEACH (EPA), PRZM (EPA), LEACH (Cornell University), and HYDRUS (International Groundwater Modeling Center). All four codes (listed here roughly in order of complexity and user expertise required, with VLEACH being least complex and HYDRUS being the most complex) compute the downward movement of water (flow) and contaminants (transport). Each is strictly one-dimensional: only downward movement is considered. Horizontal or inclined movement through the unsaturated zone is not considered. (HYDRUS can be adapted for 2-dimensional evaluations, however). These codes are designed specifically to determine the amount of sorption and degradation that occurs in soils and in the unsaturated zone, and are typically used to compute the residual, non-degraded mass of a contaminant that arrives, over time, at the water table. These models are excellent tools to predict water flow and contaminant transport under specific hydrogeologic conditions in the unsaturated zone, in particular those that are highly layered (heterogeneous), and for chemicals that undergo multiple chemical processes or chemical reactions. For vulnerability assessments, these models are sometimes applied to evaluate the attenuation capacity within and travel time through the unsaturated zone above the water table. Subregions or sections with similar unsaturated zone properties are selected and grouped. One simulation is performed for each group or section and the results mapped in various ways, e.g., a map of the travel time to the water table (perhaps specific to a contaminant), a map of the percent removal of a contaminant within the vadose zone, etc.

The most common computer code used for groundwater modeling (in all three dimensions) is MODFLOW (USGS). This and other 3D computer models can be used for highly specific site studies of groundwater contaminations that are far beyond the purpose of a typical vulnerability assessment. The data requirements for running these models are tremendous and require careful data preparation and data processing, particularly in a fully three-dimensional simulation. Sometimes, groundwater models are used to explicitly compute the complex source area of the water reaching a well. In that case, the same computer model can also be used to compute specific vulnerability for particular contaminants of concern or for specific PCAs within the source area of the well. If a well-calibrated and well-documented groundwater model exists, it may be preferable to utilize the groundwater model to address specific vulnerability issues rather than to use a basic index or a scoring-based vulnerability assessment.

Statistical Methods

Few statistical methods have been developed for vulnerability assessment, primarily because they rely on large data sets from regions already contaminated. The key to the development of a statistical method is a large, high quality data set of a specific contaminant or several specific contaminants commonly found in a region. That data set is then correlated in one fashion or another to specific properties of the subsurface (depth to water, soil permeability, slope, hydraulic conductivity, etc.) to create a statistical predictive model that can be used to make a quantitative statement about the contamination risk, such as: "if this kind of unsaturated zone, aquifer, and land use properties exist in a location, then the risk for groundwater contamination is X percent, with a confidence interval of plus or minus Y percent".

CALVUL (Troiano et al., 1999)

In California, a statistical method has been developed by the Department of Pesticide Regulations (DPR) to determine the specific vulnerability of groundwater to pesticide residues. The method is nicknamed CALVUL (California Vulnerability approach, Troiano et al., 1999). DPR uses the vulnerability analysis to determine, for each section of agricultural land in California, whether groundwater in that section of land is vulnerable or not. If it is vulnerable, the land section (square mile) becomes part of a groundwater protection area (GWPA), a term that has been formally defined by DPR: "'Groundwater protection area' means an area of land that contains soils that have been determined by the director, in consultation with the county agricultural commissioner, to be sensitive to the movement of pesticides to ground water."

The DPR method distinguishes two types of vulnerability: (1) vulnerability to pesticide leaching in coarse soils with shallow water table, and (2) vulnerability to pesticide runoff over hardpan soils (and subsequent leaching in dry wells). Within the groundwater protection zones, certain pesticide management practices must be followed, depending on whether pesticide leaching or pesticide runoff is of concern.

How is the vulnerability determined with CALVUL? Originally, the department's regulations declared vulnerable any section of land that had a qualified detection of pesticide residue in groundwater. That method was found to be unsatisfactory, because it did not encourage application of mitigation measures until the contamination had already occurred. The pesticide database for the San Joaquin Valley was used to determine the statistical relationship between pesticide residue occurrence in groundwater and a large number of soil (unsaturated zone) properties, including water holding capacity, texture, organic matter content, permeability, shrink-swell potential, slope, infiltration, etc. By determining what soil and geographic properties are good predictors of pesticide residue occurrence in groundwater, the statistical model can be used to identify sections of land that have similarly "vulnerable" soil and geographic conditions but no past or current pesticide residue detections (Troiano et al., 1999). Presumably, the most vulnerable areas are identified and can be targeted for implementation of mitigation management practices.

In principle, the CALVUL approach is identical to the vulnerability assessment in DRASTIC or in the DWSAP analysis: environmental factors are aggregated (combined) to make a determination of which areas are vulnerable and which areas are not vulnerable. Here, however, factors are aggregated by utilizing a statistical model. In DWSAP or DRASTIC, factors are aggregated by utilizing an expertly-derived scoring system. Because it is based on actually measured contamination, the statistical analysis lends the approach quantifiable credibility and validity that is not available with the index-and-overlay methods.

Texas Case Study (Evans and Maidment,1995)

In Texas, a statistical analysis similar to DPR's San Joaquin study, albeit based on a different set of statistical tools, was developed by Evans and Maidment (1995). Instead of pesticide residues in groundwater, this method uses an analysis of nitrate in groundwater as the basis for delineating vulnerable groundwater areas. As in CALVUL, the assumption made by the developers of the method was that where high contamination exists, the aquifer is more vulnerable than elsewhere. Nitrate was used as the target variable because a large amount of data was available throughout Texas and because nitrate is neither sorbed nor signifantly degraded in groundwater (except under anaerobic conditions). The analysis was done by using data from the entire state. The analysis units in this model are individual 7.5 minute maps. (Compare: the analysis units in CALVUL are land sections and the analysis unit in the DWSAP method is the protection area of a well.)

From a 30-year statewide database, the probability (risk) that a well would have nitrate levels in excess of some threshold value (1, 2, 5, or 10 mg/l NO3-N) was computed separately for each analysis unit. The exceedance probability is used as a quantifiable measure of vulnerability: the higher the chances that nitrate is found in wells within an analysis unit (area), the higher the vulnerability must be. For example, if 4 out of 12 wells within an analysis unit exceeded the threshold level, then the risk was computed as 4/12 = 0.333. This exceedance probability was then correlated to the unsaturated zone thickness, to the organic matter content, the amount of precipitation, and the amount of fertilizer sales (as a surrogate for contaminant source presence). Results were compiled statewide as well as for individual aquifer basins. The regression model developed from the correlation analysis showed no significant correlation between vulnerability (nitrate exceedance probability) and any of the indicator variables except depth to water table. However, there was significant correlation between vulnerability and aquifer basin, indicating that the different regional aquifers investigated had significantly different vulnerability. From least to most vulnerability, the four aquifer types were ranked as follows: deep bedrock (14%), shallow bedrock (37%), deep unconsolidated (46%), and shallow unconsolidated (49%), where numbers in parentheses indicate the exceedance probability for 1 mg/l NO3-N.

This study illustrates that overall results of the statistical analysis follow the general patterns laid out by the index-and-overlay methods, at considerable higher expense.

How to Decide Which Method Works Best

The decision of which method to use will depend primarily on the objectives of the vulnerability analysis. It also depends on the available data and the available funding. In defining the objectives, it is important to consider what needs to be achieved with the vulnerability analysis, who will use the results of the analysis, what decisions it will influence, and what the cost will be if a wrong decision is made because of inadequate or poor information. That cost should be weighed against the cost of an appropriately implemented vulnerability assessment.

Index-and-overlay methods probably will continue to be the main staple for vulnerability mapping. They are most suited for application by planning departments and non-hydrologically-trained users, since the decision tree comes in a "black box". However, the interpretation of the results requires some professional judgment, which can be sought as part of the vulnerability assessment.

Process modeling with computer methods will work best where the hydrogeology and unsaturated zone conditions are well known, where data exist for building a groundwater model, or where a well-calibrated and well-documented groundwater model is already available. If an existing groundwater model is used, one should carefully and professionally review what the model was created for, what assumptions went into the model, and how good the data are that went into the model. Groundwater models are like cars: not every model is good for every purpose (even if they all have the same basic components, namely an engine, wheels, etc.).

Statistical methods are useful where widespread contamination of pesticides or nitrates exist to build a well-founded statistical prediction model that can be used for adjacent areas. Statistical methods are usually region specific and not suitable for transfer to other, geographically different regions. Unlike index methods, the statistical method implies a certain degree of validation and quantifiable measure of vulnerability.

After the Assessment: Verification and Post-Audit

Verification refers to some independent procedure that can verify the results of the vulnerability analysis. *Post-audit* is essentially the same as verification, but typically occurs years later, when additional data have been sampled that can be compared to the predictions made by the vulnerability analysis.

Verification and post-audits of vulnerability assessments can be done in many different ways. The most common approach, particularly for verification of assessments done with index-and-overlay methods, is to compare the vulnerability map with the actual occurrence of some common pollutant in groundwater. Typical pollutants used are nitrate and pesticides. However, such verification works well only where the appropriate pollution source is actually present and has been present for some time.

For Further Reading

- Blodgett, R. 1993. *Drinking Water Vulnerability Assessments in Texas*, Proceedings, 1993 Annual Conference, American Water Works Association.
- Evans, Thomas A., and David R. Maidment. 1995. *A Spatial and Statistical Assessment of the Vulnerability of Texas Groundwater to Nitrate Contamination.* Technical Report CRWR 260, Center for Research in Water Resources, Bureau of Engineering Research, The University of Texas at Austin, Austin, TX. 257p.
- Holtschlag, D. J., and C. L. Luukkonen. 1998. Assessment of ground-water vulnerability to Atrazine leaching in Kent County, Michigan: Review, comparison of results of other studies, and verification, *Water-Resources Investigations Report 98-4006*, U.S. Geological Survey, Lansing, MI. 32p.
- Robins, N. S. (ed.). 1998. *Groundwater Pollution, Aquifer Recharge and Vulnerability*. Geological Society Special Publication No. 130, Geological Society, London, GB. 224 p.
- Snyder, Daniel T., J. M. Wilkinson, and L. L. Orzol. 1998. Use of a ground-water flow model with particle tracking to evaluate ground-water vulnerability, Clark County, Washington, *Water-Supply Paper 2488*, U.S. Geological Survey, Denver, CO, 61 p.
- Troiano, J., F. Spurlock, and J. Marade. 1999. *Update of the California Vulnerability Soil Analysis for Movement of Pesticides to Ground Water*. October 14, 1999. Department of Pesticide Regulation, Sacramento, CA 95814-3510, Document EH 00-05. Document available on the internet: http://www.cdpr.ca.gov/docs/empm/pubs/ehapreps/eh0005.pdf
- Vrba Jaroslav and Alexander Zoporozec (eds.). 1994. *Guidebook on Mapping Groundwater Vulnerability*. International Association of Hydrogeologists: International Contributions to Hydrogeology Volume 16, Verlag Heinz Heise, Hannover, Germany, 129p.