# Aquifer Vulnerability Analysis for Water Resource Protection

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## Abstract

As part of its statewide wellhead protection program, the Indiana Department of Environmental Management (IDEM) desired to evaluate the *aquifer vulnerability* for wellhead areas within the state of Indiana. This desire was the result of the need to satisfy the requirements of the *Source Water Assessment Plan* for the State of Indiana, which set as one of it's goals, the need for such an evaluation in order to aid the State in future planning and prioritization activities. This paper describes the aquifer vulnerability analysis protocol that was developed to assess the vulnerability of drinking water supplies to pollutant releases within wellhead protection areas. The protocol is based on information already contained in each public drinking water supply's Wellhead Protection Plans (WHPs) submitted to the State. This protocol includes the use of an *Aquifer Vulnerability Index* (AVI) that relates to the geologic, hydrogeologic and pollutant source conditions present in the wellfield and an *Aquifer Vulnerability Matrix*, which provides low, moderate and high classification ranges for expected wellfield conditions. The protocol has proven to be a valuable tool for providing an objective, semi-quantitative relative ranking system for aquifer vulnerability.

## Introduction

Concern for aquifer vulnerability to near-surface chemical releases from human activity has been a topic of interest since efforts to improve the siting of landfills in the early 1980s prompted regional scale evaluations by federal and state geologic surveys and local planners. Within the last ten years, as Wellhead Protection Plans (WPPs) have been developed by small to large size municipalities and utilities, the susceptibility of aquifers to various land development activities and point sources of contamination has again received increased attention. The need for the development of wellhead protection education programs for residents and businesses located in wellfields has also prompted a review of aquifer systems by many states and cities, with an eye toward allocation of appropriate budgets and resources to focus on those areas with the highest potential for chemical impacts. As such, the development of a simple, yet scientifically-based methodology for providing a relative ranking of wellfield vulnerability is again of current interest. The use of such a protocol in the statewide prioritization of wellhead management plan implementation also allows for the development of more effective contingency plans, especially when considering alternate short- and long-term drinking water supplies for those systems that are the most vulnerable.

# Aquifer Vulnerability Protocol

The vulnerability analysis of a Community Public Water Supply System (CPWSS) can be conducted considering the following wellhead factors:

1. ***Hydrologic and hydrogeologic conditions***: The degree of protection from fine-grained geologic barriers above the pumping well screen (i.e., the presence/absence and thickness of fine-grained sediments).
2. ***Potential contaminant sources (PSCs)***: number (and proximity) of PSCs within the delineated wellhead area (determined herein to be within the 5-year time of travel (TOT) zone)
3. ***Categories/types of contaminants***: distribution of type of contaminant source classifications within the delineated area.

The following steps have been developed for incorporating this type of available information into a system for evaluating aquifer vulnerability:

**Step 1**: Review the geological and hydrogeological data (vicinity well logs; geologic maps) provided in the WHPPs to obtain information regarding the distribution and thickness of geologic barriers above the supply well screens (factor 1).

**Step 2**: Review the PSC inventories, the landuse and PSC maps for information summarizing the number and proximity of the PSC (factor 2) for each of the wellhead protection areas.

**Step 3**: Review the PSC inventories specifically for information on the categories of contaminants (factor 3) and rank the contaminant categories using Table 1.

**Table 1. Contaminant Categories in a Wellfield**

| Contaminant Categories/Types | | | | |
|---|---|---|---|---|
| **Industrial (1)** | **Commercial (2)** | **Waste Management (3)** | **Agricultural (4)** | **Residential (5)** |
| Asphalt Plants | Airports | Hazardous waste management units (e.g. landfills, land treatment areas, surface impondments, waste piles, incinerators, | Animal burial areas | Fuel storage systems |
| Chemical manufacture, warehousing | Auto repair shops | Municipal Incinerators | Animal Feedlots | Furniture and wood strippers and refinishers |
| Electrical and electronic products and manufacturing | Boat yards | Municipal Landfills | Chemical application (e.g. pesticides, and fertilizers) | Household haardous products |
| Electroplating and metal fabrication | Construction areas | Municipal waste water and sewer lines | Chemical Storage Areas | Household lawns (chemical application) |
| Foundaries | Car washes | Open burning sites | Irrigation | Septic systems, cesspools, water softeners |
| Machine and metal working shops | Cemeteries | Recycling and reduction facilities | Manure spreading and pits | Sewer/Septic Lines |
| Manufacturing and distribution of cleaning supplies | Dry cleaning establishments | Stormwater drains, retention basins, transfer stations | | Swimming pools (e.g. chlorine) |
| Mining | Educational institutions (e.g. labs, lawns and chemical storage areas | State Confined Feeding Animal Operation (CAFO) | | |
| Petroleum production and storage and distribution centers | Gas stations | | | |
| Pipelines (e.g. oil, gas, coal, slurry) | Golf courses (chemical application) | | | |
| Septage lagoons and sludge | Jewelry and metal plating | | | |
| Storage Tanks (above-ground, below-ground,underground) | Laundromats | | | |
| Toxic and hazardous spills | Medical Institutions | | | |
| Wells-opearting and abandoned (e.g. oil, gas, water supply, injection, monitoring and exploration) | Paint shops | | | |
| Wood preserving facilities | Photography establishments/printers | | | |
| | Railroad tracks and yards/maintenance | | | |
| | Research laboratories | | | |
| | Road deicing operations (e.g. road salt) | | | |
| | Road maintenance depots | | | |
| | Scrap and junkyards | | | |
| | Storage tanks and pipes (above ground, below ground, underground) | | | |

**Notes:**
The contaminant categories/types are ranked from 1 (highest potential to contaminate) to 5 (lowest potential to contaminate)
Source: Indiana's Source Water Assessment Plan, 1999, 21pp.

**Step 4**: Determine the aquifer vulnerability using Figure 1, the '*Aquifer Vulnerability Matrix*'. The matrix determines system susceptibility based on the local geology and the well's vulnerability to contamination based on the number, proximity and type of PSC.

| | Low Geologic Sensitivity | Moderate Geologic Sensitivity | High Geologic Sensitivity |
|---|---|---|---|
| Low Contaminant Vulnerability | BT > 30 feet<br>PSCs = 0 - 5<br>CT = 4, 5<br>(AVI = 0) | BT = 15 - 30 feet<br>PSCs = 0 - 5<br>CT = 4, 5 | BT = 0 - 15 feet<br>PSCs = 0 - 5<br>CT = 4, 5 |
| Moderate Contaminant Vulnerability | BT > 30 feet<br>PSCs = 5 - 20<br>CT = 2, 3 | BT = 15 - 30 feet<br>PSCs = 5 - 20<br>CT = 2, 3 | BT = 0 - 15 feet<br>PSCs = 5 - 20<br>CT = 2, 3 |
| High Contaminant Vulnerability | BT > 30 feet<br>PSCs > 20<br>CT = 1 | BT = 15 - 30 feet<br>PSCs > 20<br>CT = 1 | BT = 0 - 15 feet<br>PSCs > 20<br>CT = 1<br>(AVI = 1) |

**Notes:**
BT = Barrier Thickness, thickness ranges selected based on confidence in level of protection.
PSCs = Number of potential contaminant sources in the 5-year TOT zone.
CT = Contaminant Type (Category 1, 2, 3, 4 or 5 in Table 1)

Barrier thickness ranges selected based on confidence in barrier distribution and effectiveness. The PSC number ranges were selected based on calcuated average (mean) and standard deviation of number of PSCs observed in the 5-yr TOT zones provided in the WHPPs.

**Figure 1. Aquifer Vulnerability Matrix**

The matrix is used for determining system susceptibility considering a) aquifer sensitivity based on local geology and b) the well's vulnerability to contamination based on the number, type, and proximity of PSCs. The matrix illustrates that 'low geologic sensitivity' (BT > 30 feet) and 'low contaminant vulnerability' (PSCs = 0 to 5 and CT = 4,5) reflect very low/no aquifer vulnerability (AVI = 0). Similarly 'high geologic sensitivity' (BT = 0 to 15 feet) and 'high contaminant vulnerability' (PSCs > 20 and CT = 1) reflect high aquifer vulnerability (AVI = 1). The matrix demonstrates a gradient of increasing aquifer vulnerability from the top left hand cell of the matrix (AVI = 0) towards the bottom right hand cell (AVI = 1), and provides an effective means to summarize vulnerability assessments.

**Step 5**: Calculate the '*Aquifer Vulnerability Index, AVI*' for each wellhead area using the following modus operandi:

## Aquifer Vulnerability Index (AVI) Calculations:

(Spreadsheet Example: for a geologic barrier of 15 feet, No. of PSCs = 9, and type of PSC = agricultural)

Given:

*Geologic Sensitivity - Barrier Characterization*

Geologic Factor, $W_1$ = **1** INPUT

| | | | |
|---|---|---|---|
| note: | $W_1$ = | 0 | (BT > 30 feet) |
| | $W_1$ = | 0.5 | (BT = 15 - 30 feet) |
| | $W_1$ = | 1 | (BT = 0 - 15 feet) |

*Potential Contaminant Sources Number*

PSC No. Factor, $W_2$ = **0.5** INPUT

| | | | |
|---|---|---|---|
| note: | $W_2$ = | 0 | (PSC No. = 0 - 5) |
| | $W_2$ = | 0.5 | (PSC No. = 5 - 20) |
| | $W_2$ = | 1 | (PSC No. > 20) |

(Note: Count all residential sewers as contributing to PSC No. = 1; count all residential septics/sewers as contributin

*Potential Contaminant Sources Characterization*

PSC Type Factor, $W_3$ = **0.5** INPUT

| | | | |
|---|---|---|---|
| (Refer to Table 1 ) note: | $W_3$ = | 0 | (CT = 4, 5; agricultural, residential) |
| | $W_3$ = | 0.5 | (CT = 2, 3; commercial, waste management) |
| | $W_3$ = | 1 | (CT = 1; industrial) |

Assumptions: Weighting Factor for geologic barrier, $\alpha_1$ = **0.6** INPUT

(Note: A thick geologic barrier is given more weightage as compared to no/low number of PSCs, since PSC have a potential to increase with time.)

Weighting Factor for PSC No., $\alpha_2$ = **0.2** INPUT

Weighting Factor for PSC Type, $\alpha_3$ = **0.2** INPUT

Calculations:

Aquifer Vulnerability Index, AVI = $(\alpha_1 W_1 + \alpha 2\, W_2 + \alpha 3\, W_3)$

AVI = **0.80** OUTPUT

Rating:

| AVI Range | Aquifer Vulnerability |
|---|---|
| 0 < AVI < 0.25 | LOW |
| 0.25 < AVI < 0.75 | MODERATE |
| 0.75 < AVI < 1 | HIGH |

(In the above example, AVI = 0.5, which would be considered **a HIGH** Aquifer Vulnerability.

Notes:

BT = Barrier Thickness

PSC No. = Number of potential contaminant sources in the 5-year TOT zone

CT= Contaminant Type (category)

Date of Last Spreadsheet Modification: 09/08/03

Spreadsheet Author: Leena A. Lothe and John A. Mundell, MUNDELL & ASSOCIATES, INC.

**Step 6**: Classify the aquifer vulnerability based on the AVI as follows:

| AVI Range | Aquifer Vulnerability |
|---|---|
| 0 < AVI < 0.25 | Low |
| 0.25 < AVI < 0.75 | Moderate |
| 0.75 < AVI <1 | High |

**Step 7:** Summarize the aquifer vulnerability and AVI data for each CPWSS, and rank utilities accordingly (i.e., low, moderate, or high aquifer vulnerability).

## Weighting Factor Assignment

The weight given to the various factors is dependent on specific preferences of the evaluating entity. A thick geologic barrier might be given more weight as compared to no/low number of PSCs, since the number of PSCs have the potential to change with time. A thick geologic barrier indicates a lower aquifer vulnerability irrespective of the number or type of PSCs. On the other hand, a thin or no barrier thickness indicates a high aquifer vulnerability, even if there is a low number of PSCs. These factors can be taken into account by weighting them to calculate the AVI. For the protocol recommended, the following weights were used:

Weighting Factor for geologic barrier, $\alpha_1 = 0.6$
Weighting Factor for PSC No., $\alpha_2 = 0.2$
Weighting Factor for PSC Type, $\alpha_3 = 0.2$

## Example Aquifer Vulnerability Calculations

To provide a demonstration of the methodology proposed, three examples of actual utility systems will be provided that covered the range of low to high aquifer vulnerability.

<u>**Town A**</u> has ***35 to 40 feet*** of clay above the production well screened interval, and ***2*** potential sources of contamination (PSCs) within the 5-year time of travel (TOT) zone. The type of PSCs are predominantly ***industrial,*** and the town is on a ***septic system.***

1. As per the geologic sensitivity-barrier characterization, in this case, the geologic factor '***W1' = 0*** since the Barrier Thickness, BT > 30 feet.
2. The PSC No. Factor '***W2***'= ***0*** , since PSC No. = 0 to 5. Note that all residential sewers count as contributing to PSC No. = 1.
3. The PSC Type Factor, ***'W3' = 1*** , since CT = 1; industrial.

Then, AVI = ($\alpha$1 W1 + $\alpha$2 W2 + $\alpha$3 W3) = (0.6(0) + 0.2(0) + 0.2(1) = ***0.2.*** This categorizes the system as having a ***'low'*** vulnerability.

**<u>Town B</u>** has ***25 to30 feet*** of clay above the well intake, and ***23*** PSCs within the 5-year TOT. The type of PSCs are predominantly ***industrial,*** and the town is on a ***sewer system.***

1. As per the geologic sensitivity-barrier characterization, the geologic factor '***W1' = 0.5,*** since the BT = 15 - 30 feet.

2. The PSC No. Factor '***W2***'= ***1,*** since PSC No. > 20.

3. The PSC Type Factor, ***'W3' = 1***, since CT = 1; industrial.

Then, AVI = (0.6(0.5) + 0.2(1) + 0.2(1)) = ***0.7***. Therefore, the system has a ***'moderate'*** vulnerability.

**<u>Town C</u>** has ***0 feet*** of overlying clay, and ***16*** PSCs within the 5-year TOT zone. The type of PSCs are predominantly ***industrial,*** and the town was on a ***sewer system.***

4. As per the geologic sensitivity-barrier characterization, the geologic factor '***W1' = 1***, since BT = 0 to 15 feet.

5. The PSC No. Factor '***W2***'= ***0.5*** , since PSC No. = 5 to 20.

6. The PSC Type Factor, ***'W3' = 1*** , since CT = 1; industrial.

AVI = (0.6)(1) + 0.2 (0.5) + 0.2 (1) = ***0.9.*** Therefore, the system is rated as one with a '***high***'vulnerability.

## Conclusions

The proposed aquifer vulnerability ranking protocol has proven to be an effective, flexible tool for providing an objective, semi-quantitative relative ranking system for utility systems using limited data available in most wellfield protection plans. The use of both an *Aquifer Vulnerability Index* (AVI) and an *Aquifer Vulnerability Matrix* allows a technically sound framework within which wellfield ranking can help guide the local decision-making of governmental agencies in developing strategies for the management of the public water supply, whether it be through stronger institutional controls, the passage of local ordinances, or concerted educational programs for citizens and businesses.

## References


1. Indiana Department of Environmental Management (IDEM). 1996. " 327 IAC 8-4, "Indiana Wellhead Protection Rule".

2. Indiana Department of Environmental Management (IDEM), 2000, " *Source Water Assessment Plan*", p. 22-23.