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# Groundwater Vulnerability Assessments and Integrated Water Resource Management

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## Introduction

Canada has a disproportionate share of the world's water and, as such, many Canadians hold the mistaken belief that our renewable freshwater resources are unlimited. Also, as groundwater is "hidden" below ground, it is hard to understand the processes affecting the resource. Groundwater is vulnerable to contamination from human activities, and is very difficult to remediate once contaminated. British Columbia has over 900 developed aquifers and almost 750 000 British Columbians (about 20% of the population) rely on groundwater as their drinking water source (BC Ministry of Environment 2009). To properly manage and protect the resource, it is therefore important to determine areas where groundwater may be more vulnerable to contamination.

"Vulnerability" is the degree to which human or environmental systems are likely to experience harm due to perturbation or stress, and can be identified for a specified system, hazard, or group of hazards (Popescu et al. 2008). In hydrogeology (the study of groundwater), vulnerability assessments typically describe the susceptibility of the water table, a particular aquifer, or a water well to contaminants that can reduce the groundwater quality (e.g., nitrates, industrial chemicals, gasoline). The contaminants may originate from a natural source (e.g., rock containing arsenic) or be introduced by human

activity (e.g., agriculture: fertilizers; industry: chemical storage and spills).

Groundwater vulnerability assessments often result in a map of areas where the resource is vulnerable to contamination from surface activities.

Vulnerability assessments prioritize areas for further investigation, protection, and monitoring. As part of integrated water resource management, vulnerability assessments are integrated into a program of groundwater characterization and risk analysis, with tiered approaches

for assessing vulnerability, hazard potential, and risk. Vulnerability assessments are also powerful educational tools for raising public awareness of groundwater protection issues, which is an on-going need (Nowlan 2005).

This article provides a synopsis of groundwater vulnerability to contamination with a particular focus on methods and uses of vulnerability maps, and considers the importance of groundwater

*As part of integrated water resource management, vulnerability assessments are integrated into a program of groundwater characterization and risk analysis, with tiered approaches for assessing vulnerability, hazard potential, and risk.*

vulnerability and protection in the context of integrated water resources management. Numerous communities in British Columbia have undertaken vulnerability assessments for the purpose of water resource management. This article also provides an overview of some of these studies including the Fraser Valley (Wei 1998), Langley (Golder Associates 2005), Gulf Islands (Denny et al. 2007), Oliver (Liggett et al. 2006), and Vancouver Island (Liggett and Gilchrist 2009). The British Columbia Aquifer Classification System is also briefly described.

## Groundwater Vulnerability: An Overview

### What is Groundwater Vulnerability?

No single standardized definition for groundwater vulnerability exists; however, the concept describes the relative ease with which the groundwater resource could be contaminated. This is based on the idea that the physical environment can provide the resource with some degree of protection from contamination. Groundwater vulnerability has been defined as “an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts” (Vrba and Zaporozec 1994:7). The National Research Council (1993:16) defines it as “the tendency or likelihood for contaminants to reach a specified position in the ground water system after introduction at some location above the uppermost aquifer.” Although it is technically feasible to assess the vulnerability of groundwater to other hazards, such as drought, overpumping, and subsurface disturbance in mines or injection wells, this article focuses on groundwater vulnerability to water quality degradation (e.g., contamination).

Groundwater can be contaminated from fertilizers, pesticides, road salt, chemical spills, septic systems, landfills, and many other human actions. It may occur in a small

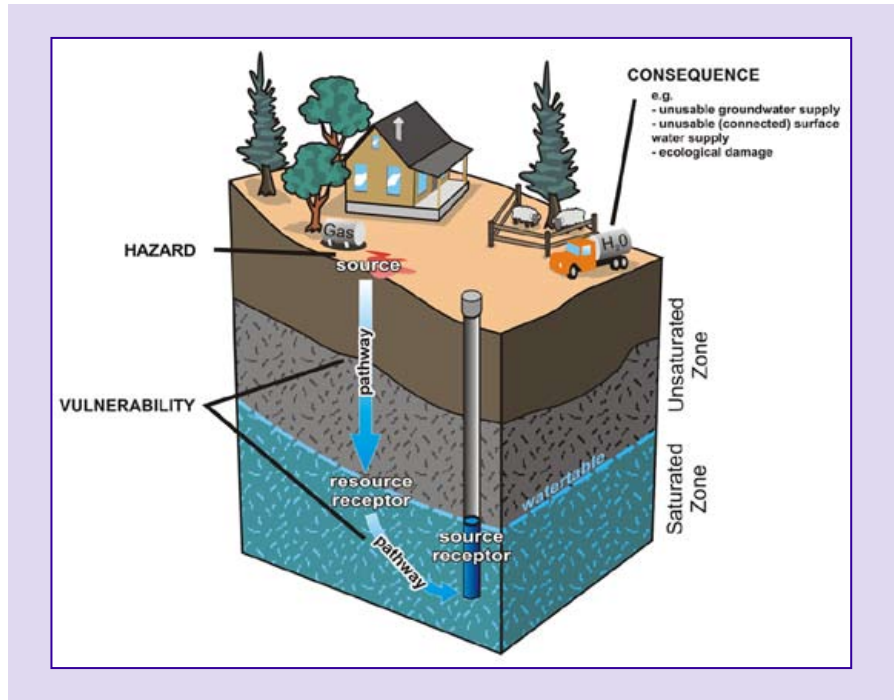


Figure 1. Source–pathway–receptor model for contaminants. The combination of vulnerability, hazard, and consequence contribute to overall risk. The vulnerability component evaluates the pathway, the hazard component evaluates the source, and the consequence evaluates the cost of losing the resource at the receptor (based on figures by B. Turner and R. Franklin, *Natural Resources Canada*).

area (e.g., a leaking gas tank) or over a very large area (e.g., from fertilizers in an agricultural area). Contaminants may also be released in a single event, or continuously over time. Once groundwater becomes contaminated, it is very difficult to remediate: groundwater moves slowly, so flushing out an aquifer can take a very long time. By mapping areas of high and low vulnerability, it is possible to identify which areas are more susceptible to contamination, and thus work to prevent contamination in the first place.

Groundwater vulnerability is related to the source–pathway–receptor model of contamination (Figure 1). A contaminant “source” (e.g., gasoline from a leaky tank) infiltrates into the ground and migrates downwards through the unsaturated zone (area above the water table where the pore space is filled with air as well as water) along a “pathway” towards the water table (the point in the subsurface where the pores become

completely filled with water). When the gasoline reaches the water table, it intersects a “receptor”: the groundwater system is a “resource receptor.” Once the gasoline is in the groundwater system, it follows another pathway, more horizontally through the saturated zone (area below the water table where the pores are completely filled with water), and can be intersected by a “source receptor,” such as a water well or spring. Groundwater vulnerability assesses the pathway portion of this model; that is, how easily contaminants can move from the source to the receptor.

Groundwater vulnerability can be determined for any point of interest in the subsurface (National Research Council 1993), but vulnerability assessments are typically performed for the water table (e.g., Stigter et al. 2006), uppermost aquifer (e.g., Liggett and Gilchrist 2009), or a particular well (e.g., Frind et al. 2006)

*Continued on page 20*

as receptors. Vulnerability assessments are usually performed in relation to contaminants released at the surface, migrating downwards through the unsaturated zone towards the water table and/or laterally through the saturated zone. The vulnerability to sources such as injection wells or underground storage tanks can also be addressed, although this article will not discuss methods for these types of assessments.

Within the scientific community, there is on-going debate about whether groundwater vulnerability is solely an intrinsic property of the land and subsurface, or whether it also encompasses properties of the contaminant type, loading, fate, and transport. Vrba and Zaporozec (1994), the Natural Research Council (1993), and the European community have recognized “intrinsic vulnerability” as the natural susceptibility to contamination based on the physical characteristics of the environment, and “specific vulnerability” as accounting for the transport properties of a particular contaminant or group of contaminants through the subsurface (Figure 2). To understand how vulnerability is characterized in an area, it is therefore important to be aware of the parameters used to assess vulnerability in a particular study.

An assessment of groundwater risk can be made with the hazard(s)—the pollution potential from the surface (e.g., types, loading, distribution, toxicity, etc.)—and the consequence of losing the resource at the receptor, in addition to the vulnerability (Figures 1, 2) (e.g., Geological Survey of Ireland 1999; Birkmann 2006). In some cases, no differentiation exists between specific vulnerability and risk assessments, with hazard types, distribution, loading, and transport all included at the risk-assessment stage (Figure 2) (e.g., Focazio et al. 2002). Other forms of risk assessment do not include the consequence factor, as this is typically a difficult parameter to quantify (e.g., Uricchio et al. 2004; Birkmann 2006). To generalize, risk

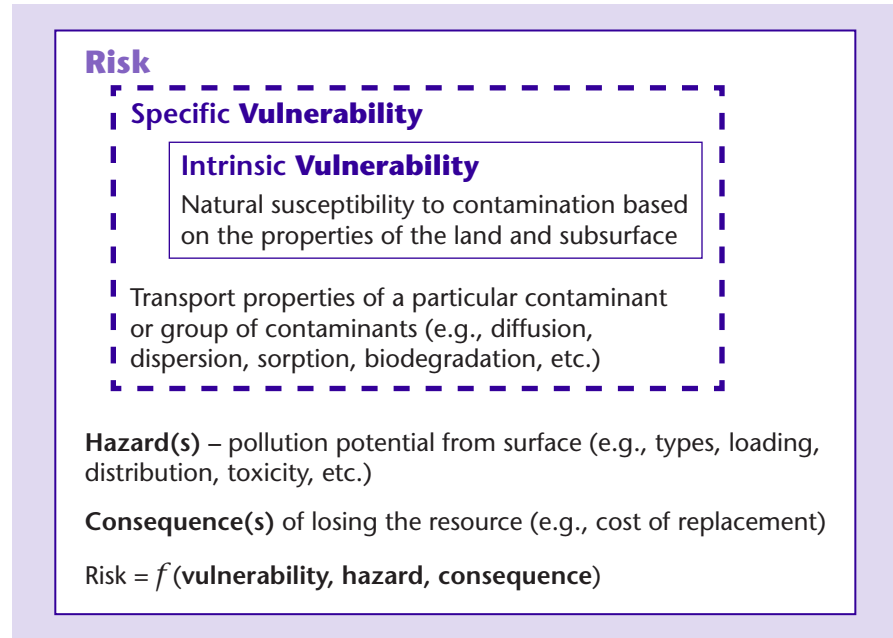


Figure 2. Progression from intrinsic vulnerability to risk assessment, with the inclusion of hazard and consequence. Specific vulnerability assessments include intrinsic properties as well as transport properties of a specific contaminant(s). Sometimes there is no distinction between the specific vulnerability and risk assessment steps (modified from Brouyère et al. 2001).

is a function of the vulnerability, hazard potential, and consequence; however, the exact indicators used, how they are combined, and what terminology is used is not consistent between scholars and practitioners. Additionally, the level of detail of vulnerability, hazard, or risk assessment may vary depending on the study.

### How are Vulnerability Assessments Performed?

Groundwater vulnerability assessments are a means to synthesize complex hydrogeologic information into a form useable by planners, decision and policy makers, geoscientists, and the public. The development of vulnerability maps is useful for many aspects of water management, including: prioritizing areas for monitoring, protection, and further investigation; and the development of risk assessments, resource characterization, and education.

Since vulnerability itself cannot be directly measured, other information such as geology, depth to water, soil types, hydraulic properties

(parameters describing water flow and storage in the subsurface), and precipitation are used to assess the relative ease with which contaminants can reach and move through the groundwater system. In addition, parameters such as depth to water and hydraulic conductivity may be extrapolated, based on known points, to areas with limited or no data.

Many methods integrate such information to determine the vulnerability. The methods vary from simple, qualitative, inexpensive, indexing assessments to complex,

*Groundwater vulnerability assessments are a means to synthesize complex hydrogeologic information into a form useable by planners, decision and policy makers, geoscientists, and the public.*

qualitative, costly, numerical modelling assessments (Focazio et al. 2002). The approach used to determine vulnerability for a particular project will depend on numerous factors, including the purpose and scope of the study, scale, data availability, time, cost, and end-user requirements.

In general, vulnerability assessments are categorized as:

- index (and overlay) methods,
- statistical methods, or
- process methods (Gogu and Dassargues 2000; Focazio et al. 2002).

Table 1 provides examples of each of these three methods and they are discussed in turn below.

Indexing methods are very popular because they are easy to implement, inexpensive to produce, use readily available data, and often produce categorical results (Focazio et al. 2002). Index methods also assess vulnerability spatially over large regions and can therefore show the vulnerability of the water table or uppermost aquifers in a region (i.e., resource receptor). In index-based methods (Figure 3), parameters depicting the physical properties of the system, such as depth to water and lithology, are mapped based on either existing data sets (e.g., well data, geological maps) or field data. Subjective numerical values or ratings are then assigned to each parameter map. The rated maps are combined to produce a relative indication of the vulnerability spatially over an area. In most cases, the vulnerability value is categorized into a set number of categories (e.g., three categories: high, medium, low; Figure 3). With the use of a geographical information system (GIS), digital maps of each parameter are easily rated and combined to produce the final vulnerability map. Index-based methods are best suited to produce regional-scale screening tools for use in decision making, and for prioritizing focus areas and level of site assessments. These methods are limited

**Table 1. Selected examples of vulnerability mapping methods. Light purple boxes indicate parameters included in a given method; grey boxes indicate parameters are not included. Dark blue boxes indicate possible inclusion of parameters, which will depend on the actual study.**

Name and reference	Type <sup>a</sup>	Examples	Parameters <sup>b</sup>						
			D	R	A	S	U	O	
<i>Index Methods</i>									
DRASTIC (Aller et al. 1987)	INV	Al-Hanbali and Kondoh (2008), Draoui (2008), Liggett et al. (2006)							
GOD (Foster 1987)	INV	Gogu et al. (2003), Neukum and Hötzl (2007)							
EPIK (Doerfliger et al. 1999)	INV	Vías et al. (2005), Neukum and Hötzl (2007)							
Aquifer Vulnerability Index (AVI) (Van Stempvoort et al. 1993)	INV	Wei (1998), Alberta Land Resource Atlas of Alberta (2009)							
<i>Statistical Methods</i>									
Logistic Regression (Helsel and Hirsch 1992)	SPV	LaMotte and Greene (2007), Antonakos and Lambrakis (2007)							
<i>Process Methods</i>									
Surface to Aquifer/Well Advection Time (SAAT/SWAT) (Ontario Ministry of the Environment 2006)	INV	N/A							
Numerical Models (e.g., MODFLOW [US Geological Survey], FEFLOW [DHI Software])	INV or SPV	Frind et al. (2006), Butscher and Huggenberger (2008)							

<sup>a</sup> INV = intrinsic vulnerability; SPV = specific vulnerability.

<sup>b</sup> D = depth to water; R = recharge/infiltration; A = aquifer characteristics (material, conductivity, etc.); S = saturated zone characteristics (e.g., flow patterns, layering, hydraulic gradient); U = unsaturated zone characteristics (material, hydraulic conductivity, soil moisture); O = other characteristics (e.g., explicit level of confinement, karst features, permeable pathways).

because of the subjective nature of the rating schemes, and because the hydrogeologic system is not explicitly represented. Note that the availability of data and interpolation methods used affect the reliability and scale of the final map. Table 1 provides examples of indexing methods and indicates the sub-parameters used in each method.

Statistical methods of assessing vulnerability involve the calculation

of the probability of a particular contaminant exceeding a certain concentration. These methods are typically used in places with diffuse sources of contamination, such as to detect nitrates over agricultural areas. Statistical methods usually start with an analysis and mapping of water quality from known sites (e.g., samples from wells or soil). These maps can then be integrated into

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linear regression models in which the contaminant concentration is related to a series of factors such as geology, well depth, and/or land use (Focazio et al. 2002) (Table 1). Statistical methods produce spatially distributed probabilities of exceedance, rather than a categorized high, medium, and low ranking. These methods can show vulnerability to either a resource receptor (e.g., the water table) or a source receptor (e.g., a water well), and may be used instead of indexing methods when there is a specific interest for a particular contaminant over a large area and sufficient data exists on water quality in relation to the contaminant in question.

Process-based methods are powerful for assessing groundwater vulnerability. These physically based methods do not provide an output of simple relative values (Focazio et al. 2002). Instead, process-based methods use deterministic approaches to estimate time of travel, contaminant concentrations, and duration of contamination to quantify areas of high and low vulnerability (Figure 4). These approaches may include analytical solutions (e.g., Dupuit approximations) or numerical computer models (e.g., SAAT, SWAT, MODFLOW, MIKE-SHE). Some of these process-based methods include only the unsaturated zone (e.g., SAAT), and others include both (e.g., SWAT, MIKE-SHE) or only the saturated zone (e.g., MODFLOW). Additionally, process-based methods can assess groundwater flow or contaminant transport within the subsurface. The method and model of choice depends on the scope of a particular study.

Interpretation is needed to classify the results from process-based methods into specific categories of vulnerability (e.g., high, medium, low). Process-based models can show a representation of the flow system, and are ideal for determining vulnerability of a source receptor (e.g., a water well) (Figure 4); however, these methods are data-intensive and require

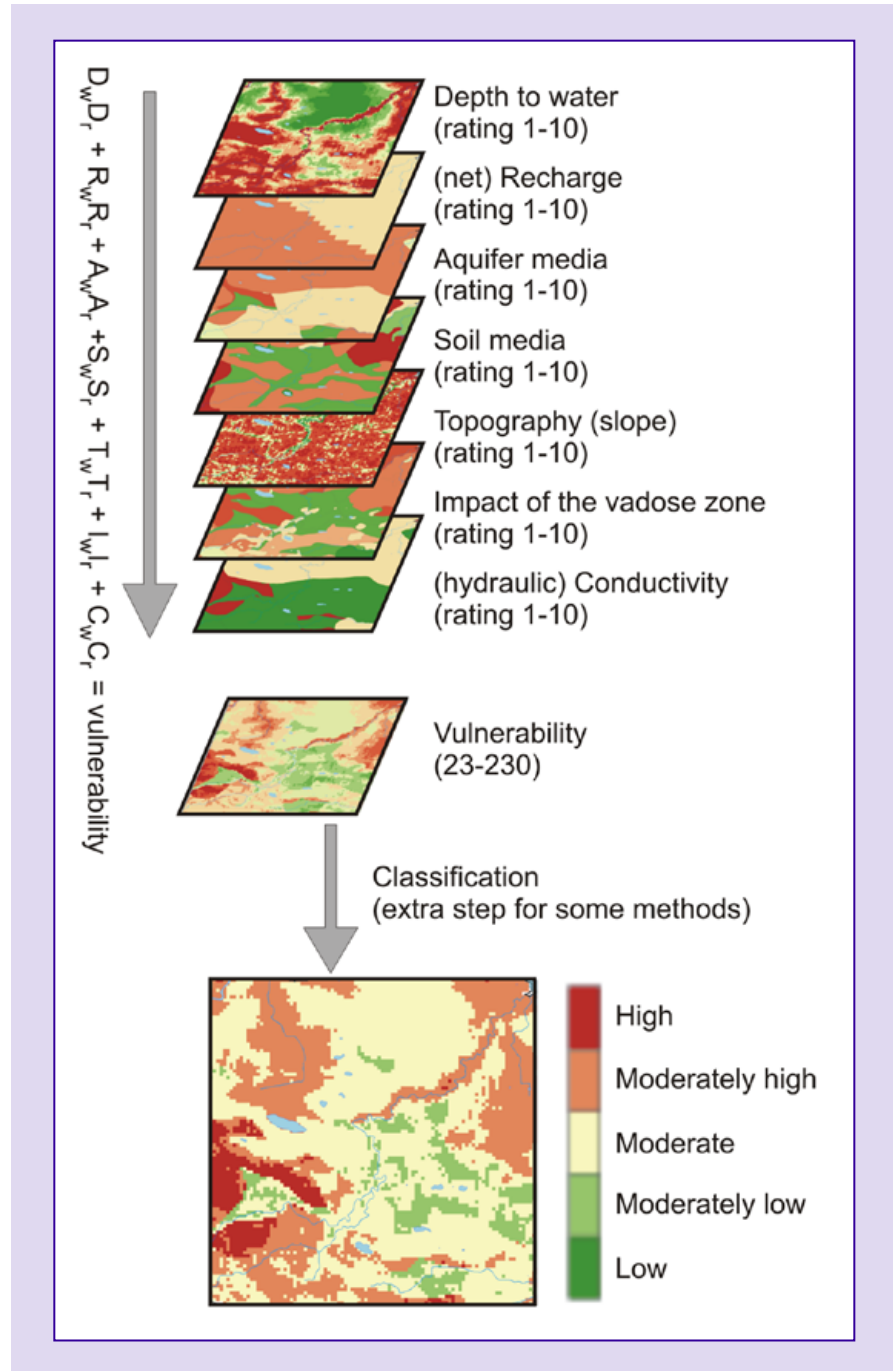


Figure 3. Example of an index method, DRASTIC, for mapping aquifer vulnerability. Each physical parameter is mapped spatially in a geographic information system with existing data sets or field data. Each map is then rated according to its effect on vulnerability, and the subsequent parameter maps are all combined into a final map. In this example, the DRASTIC equation consists of multiplying each parameter's rating (r) by a set weight (w). Also in this example, DRASTIC scores are grouped into five vulnerability categories ranging from high to low. The number of categories used to display the results can vary.

extensive resources to develop. These methods are also typically applied at local scales, to determine well vulnerability, rather than at regional scales

to a resource receptor (e.g., the water table or an aquifer; Frind et al. 2006). To illustrate how far from and in what geometry water will be drawn into the

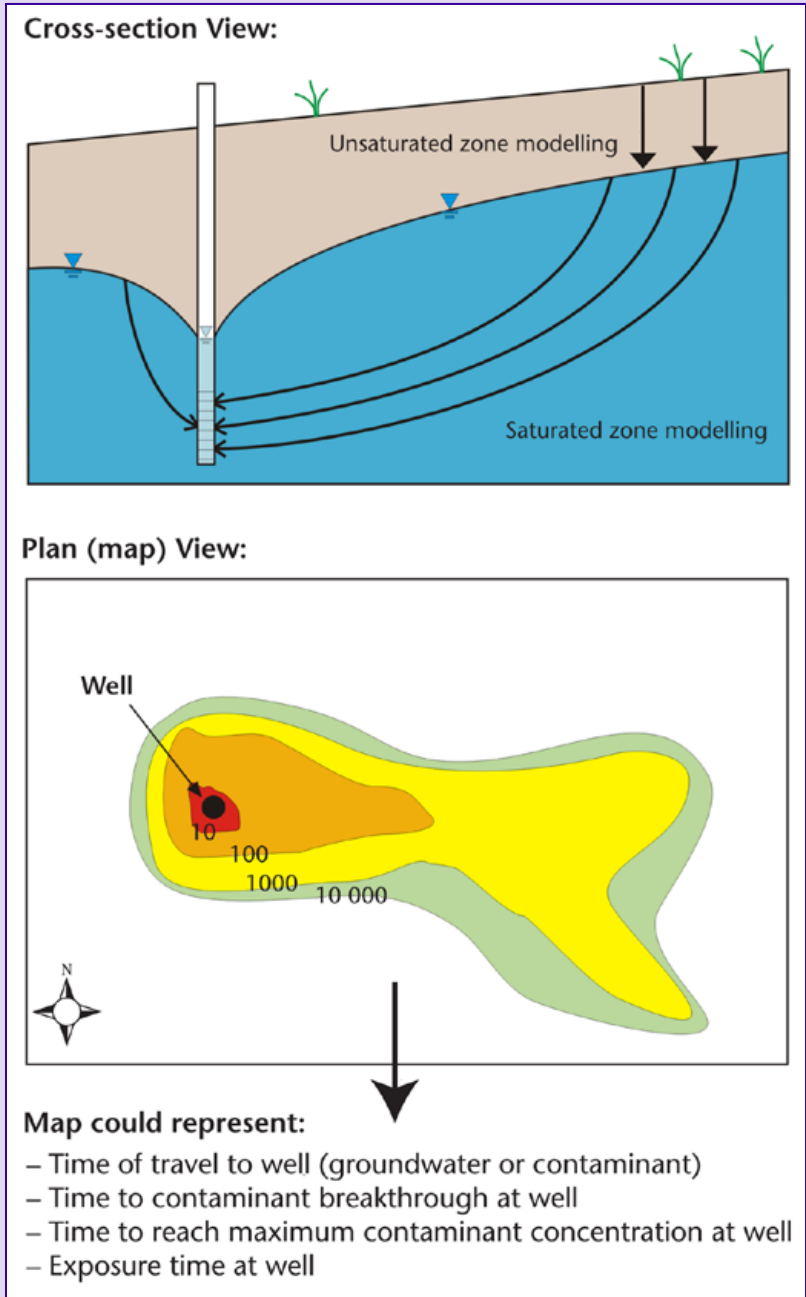


Figure 4. Schematic diagram of process-based methods of assessing vulnerability to a well. Top: Numerical modelling can show the direction, magnitude, and timing of groundwater (or contaminant) flow into a well. Bottom: Plan view of the same system showing the well capture zone outlined on the surface for purposes of well-head protection planning. Contours may represent time of travel, time to reach maximum contaminant concentration, etc.

well, numerical models are typically used to develop capture zones around municipal supply wells (Figure 4). From these capture zones, well-head protection areas can be established.

Regardless of the method used, care must be taken when interpreting vulnerability assessments and maps. The parameters used to assess the vulnerability for a particular study,

as well as the assumptions and limitations of the method, should be clearly documented and understood. In the case of index methods, the resultant vulnerability maps are not meant as a replacement for site-specific investigation. Most methods do not account for contaminants introduced below ground. Intrinsic vulnerability mapping methods do not account for specific properties of a contaminant, and do not provide an assessment of the hazard potential. For an area where intrinsic vulnerability has been mapped, a classification of low vulnerability does not mean the groundwater will not become contaminated. If a high hazard exists (e.g., intensive agriculture), then the risk and actual presence of contamination may be quite high (e.g., Stigter et al. 2006).

### Vulnerability Assessments within Integrated Water Resources Management

The management and protection of groundwater resources is only part of an overall water management strategy. Although surface water resources are often more evident to people than “hidden” groundwater resources, managing the water resource presents a challenge of navigating the interface between natural ecosystems and human influence. To effectively capitalize on the valuable information resulting from groundwater vulnerability assessments, it is helpful to consider some broad tenets for water management.

Integrated water resources management (IWRM) has been identified as a useful paradigm for the development of policies to ensure widespread access to freshwater internationally (Policy Research Initiative 2005). Here, we focus on the vulnerability of groundwater resources to contamination and identify the ways in which groundwater vulnerability assessments can form a fundamental part of IWRM.

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Integrated water resources management is a process that promotes the co-ordinated development and management of water, land, and related resources to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Global Water Partnership 2000). Even though the world's supply of freshwater is estimated at 35 million km<sup>3</sup> (Environment Canada 2004), many global citizens lack access to safe drinking water and appropriate sanitation. With such global disparities in water access and to ensure environmental sustainability, the need is reinforced to develop ways of working toward international goals for freshwater, such as those established for Agenda 21 (United Nations Conference on Environment and Development 1992) and the United Nations Millennium Development Goals.

Integrated water resources management is based on four principles that were established following an international consultative process that concluded with the International Conference on Water and the Environment in Dublin in 1992. These principles provided the foundation for the recommendations made at the United Nations Conference on Environment and Development in Rio de Janeiro later the same year. The four IWRM principles are:

1. Freshwater is a finite and vulnerable resource essential to sustain life, development, and the environment.
2. Water development and management should be based on a participatory approach, involving users, planners, and policy-makers at all levels.
3. Women play a central part in the provision, management, and safeguarding of water.
4. Water has an economic value in all its competing uses and should be recognized as an economic good.

The third principle points to the need to ensure that the water sector is gender-aware (Global Water Partnership 2000), perhaps of acute importance in less-developed countries. The fourth principle highlights the challenge of water management when water is widely viewed as a free good that arrives, for the most part, as precipitation from the skies. The first two principles are most directly relevant to this article since the first principle underscores the issue of water vulnerability and the second principle emphasizes the need for inclusive, participatory approaches to water management. At its core, IWRM is a philosophy rather than a blueprint. It acknowledges that local variability and local context will necessitate various water management strategies to sustainably manage the resource.

While watershed management approaches have become increasingly commonplace for surface water management in recent years, there has been perhaps less consideration of how groundwater is included in the overall policy development for freshwater. Indeed, the importance of groundwater protection is not often taken into account in water management (Nowlan 2005). From a potential contamination perspective, the groundwater resource may be exposed to contamination as a result of activities that take place on the land surface. At once, this implicates a tight coupling between land use decisions and groundwater resource management decisions. This coupling highlights the need for methods and evaluation strategies to determine water management options that are balanced with the commercial, industrial, agricultural, and community design directions occurring in our urban and rural landscapes throughout British Columbia. By selecting some means of evaluating groundwater vulnerability (see Table 1), we begin to bring in the groundwater piece of the larger IWRM puzzle.

The issue remains, however, of how to implement the principles of IWRM, particularly with respect to groundwater. A promising approach

is to develop guidelines that advise different courses of action under differing vulnerability circumstances. The actual implementation of the course of action may be triggered, for example, by a development permit application. Piscopo (2001) identified five vulnerability classes as well as groundwater assessment requirements for each class (Table 2). Areas classified as low vulnerability required a groundwater assessment report that was to include a desk study to identify concerns and potential risk to groundwater. In areas of moderately high vulnerability, the requirement was a demonstrated groundwater protection system, including a desk study, site investigation, and monitoring program (Piscopo 2001).

Integrated watershed management is inherently complex since it requires the synthesis of multiple spatial and temporal data sets together with the identified priorities and values of water users and water managers. The process balances many constraints and opportunities ranging from the environmental, engineering, technical, and institutional, to the jurisdictional, economical, cultural, social, and political. In practice, an intrinsic groundwater vulnerability assessment is usually performed first, and the mapping results can be used independently or integrated into further risk assessment and watershed management. Much of water management becomes a question of managing risks since variations in water flows and groundwater recharge, for example, may lead to flood events and drought. Such variations might be due to climatic conditions or land mismanagement

*The process of integrated watershed management balances many constraints and opportunities ranging from the environmental, engineering, technical, and institutional, to the jurisdictional, economical, cultural, social, and political.*





**Table 2. Example of groundwater assessment requirements for various vulnerability classifications summarized from Piscopo (2001).**

Vulnerability classification	Groundwater assessment requirements
Low	Groundwater contamination assessment report: Requires a desk study to identify hazards and risk to groundwater or the environment, and the need for any further action. A standard format hydrogeological report would most likely result.
Low-moderate	Site investigation with monitoring: Requires limited site investigation, groundwater monitoring, testing, and delineation of flow system in addition to desk study.
Moderate	Detailed site investigation and monitoring: Requires more detailed site investigation including ongoing monitoring and protection design factors (e.g., natural attenuation, physical barriers) in addition to requirements above.
Moderately high	Demonstrated groundwater protection system: The vulnerability is high enough such that a contaminant spill cannot be tolerated. Requires, in addition to the above, that protection design factors must be effectively demonstrated. A feasibility plan for remediation must be included with on-going monitoring.
High	Demonstrated remedial action plan/prohibition: Requires a remedial action plan including above and a demonstrated remedial action plan that analyzes the effectiveness of remediation in achieving designated water quality criteria, and the financial capacity of the responsible party to enact the plan. If the risk to groundwater is still unacceptable, the activity may be banned by the responsible authority.

and can have a dramatic effect on economic, environmental, and social systems (Global Water Partnership 2000). Contamination of the water resource leads to human health risks and affects ecosystem functioning, which adversely affects economic development.

Integrated water resources management is undertaken through collaborative and stakeholder-driven processes (Natural Resources Canada 2005). Land use planning processes are public processes that require input from subject area experts and concerned citizens. By linking water management, and groundwater vulnerability in particular, with land use management, an approach is created that can examine the spatial and temporal variations in land use scenarios as communities

and ecosystems grow and change over time. This represents a shift from the current status quo where “water planning currently follows from decisions about land use and economic development” (Brandes and Brooks 2007:22). In linking water planning and land use planning together, decision makers can consider a set of scenarios and select a path that is most in line with the desired future of their community. In British Columbia, official community plans can incorporate policies specifically for water management and require that well-head protection plans, best management practices, and development permit areas are included as part of the permit approvals process. Groundwater vulnerability is by no means the only criteria of importance; to make balanced decisions for

long-term water security, tradeoffs and consequences should be realistically considered and assessed to work within the complexity of human-natural systems. Vulnerability assessments are a key component of the integrated management of water resources. These assessments can help guide decision making about future development and the options available to protect and monitor the groundwater resource in the context of IWRM.

### Vulnerability Assessments in British Columbia

Several large- and small-scale assessments of groundwater vulnerability have taken place in British Columbia. Table 3 presents examples of some of the vulnerability mapping projects undertaken and their use in water resource management. These examples show various motivations behind the initiation of the vulnerability assessment project and illustrate how vulnerability maps can be used in water management.

### BC Aquifer Classification System

The British Columbia Aquifer Classification System (ACS; see detailed description on page 13 of this issue) was developed in 1994 as a means of providing:

1. a framework for directing detailed aquifer mapping and assessment;
2. a method of screening and prioritizing management, protection, and remediation over provincial to local levels;
3. identification of level of management and protection for aquifers;
4. an inventory of aquifers; and
5. increased public knowledge and understanding of groundwater resources (Kreye et al. 1994).

This system has been implemented across the province and has delineated over 900 aquifers since 1994. Once delineated, aquifers are assigned a classification and ranking value. The classification component includes an assessment of the level of intrinsic

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aquifer vulnerability and the level of development. The ranking component is calculated to prioritize aquifers for further assessment, management, and protection. The *Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater* (Berardinucci and Ronneseth 2002) provides a detailed description of the ACS, with guidelines and usage examples.

The ACS is an indexing method of mapping intrinsic aquifer vulnerability. The level of vulnerability in the classification component is assessed subjectively, based on the intrinsic characteristics of the mapped aquifer, and grouped into one of three classes (high: A; medium: B; low: C). The level of development is also subjectively assessed based on the demand versus aquifer supply, and grouped into three classes (high: I; medium: II;

low: III). The ranking value component accounts for the productivity of the aquifer, the vulnerability, aquifer size, water demand, type of water use, known or documented water quality and quantity concerns. Each of these parameters is assigned a point value (1, 2, or 3) and added to provide the ranking value. A high ranking indicates an aquifer in greater need of attention than a lower ranking. An example of the tag assigned to a particular aquifer

**Table 3. Selected vulnerability assessments in British Columbia.<sup>a</sup>**

Location	Rationale	Approach (method)	Outcome (result)
Fraser Valley (Wei 1998)	Initiated from need to determine vulnerability of aquifers in province and to compare methods of assessing vulnerability in this area.	DRASTIC and AVI Indexing method of intrinsic vulnerability mapping	Use of vulnerability maps to compare nitrate concentrations in groundwater and evaluate differences between two methods. Both methods were found suitable for assessing vulnerability in the Fraser Valley.
Langley (Fraser Valley; Golder Associates 2005)	Initiated as part of regional Water Resource Management Strategy (WRMS). The WRMS was initiated to provide an established framework for managing water quality and quantity throughout the Township.	Aquifer Vulnerability Index (AVI) Indexing method of intrinsic aquifer vulnerability	Use of vulnerability map to inform future planning and development. Opportunity to couple with groundwater flow model
Gulf Islands (Denny et al. 2007)	Initiated because of history of groundwater studies on the Islands, of water scarcity in summer months, and of saltwater intrusion. Vulnerability mapping could help focus groundwater management on the Islands.	DRASTIC-Fm Indexing method of intrinsic aquifer vulnerability Fractured media parameter added to DRASTIC to account for local hydrogeological conditions (fault and fracture flow; Surrette and Allen 2008)	Use of vulnerability map in Official Community Plan on North Pender Island, and collaboration with Natural Resources Canada and Islands Trust to provide tools for understanding groundwater on Gulf Islands. Map released as a GSC Open File for public access (#5333), and included in a community atlas through the Canadian Parks and Wilderness Society ( <a href="http://cpaws.org/files/atlas-gulf.pdf">http://cpaws.org/files/atlas-gulf.pdf</a> )
Oliver (Okanagan Valley; Liggett et al. 2006)	Initiated through collaborative sustainable development planning with Smart Growth on the Ground (Smart Growth on the Ground 2006). Process involved multiple stakeholders designing community priorities for future development. Water quality was identified as a key priority.	DRASTIC Indexing method of intrinsic aquifer vulnerability	Use of vulnerability map as layer in land use allocation model to provide scenarios of future development based on the priorities outlined by the community.
Vancouver Island (Liggett and Gilchrist 2009)	Initiated by regional health authority because of need for source water protection tools.	DRASTIC Indexing method of intrinsic aquifer vulnerability Large-scale application of methodology over all of Vancouver Island.	Potential use of vulnerability map in future land-use/water planning, source water protection, and development of guidelines and responses for vulnerability categories (e.g., high, medium, low).

<sup>a</sup> Aquifer vulnerability maps for the Gulf Islands, Okanagan, and southeast Vancouver Island will soon be available on the National Groundwater Database (<http://ngwd-bdnes.ctis.nrcan.gc.ca/>).

An example of the tag assigned to a particular aquifer is IIIA(15), where "III" indicates the level of development (low in this case), "A" indicates the level of vulnerability (high in this case), and "(15)" indicates the ranking value.

The ACS is designed for use as a screening tool to set groundwater management priorities in a standardized fashion at local, regional, and provincial levels (Kreye et al. 1994). It does not provide site-specific information, and the classification is generalized over the entire mapped aquifer. The mapping of aquifers is based on the availability of data, particularly water well data, and therefore not all areas have been mapped. Alternate methods of mapping vulnerability can be applied to areas already mapped with the ACS. Providing that sufficient data is available at a smaller scale, these methods (such as DRASTIC) may be able to show variations in vulnerability across a single aquifer mapped by the ACS. This allows the assessment of smaller-scale variations in vulnerability. Areas assessed as high vulnerability with the ACS may possibly appear as lower vulnerability when mapped using a different method on a smaller-scale, or vice versa. This is to be expected, especially since the study of a given area moves from a regional, screening tool method, to more local, site-specific methods.

## Conclusions

Groundwater vulnerability assessments provide a tool for highlighting areas where groundwater is more susceptible to contaminants introduced at the land surface. These assessments can vary from qualitative indexing methods to quantitative process methods, depending on the purpose of a study. Intrinsic vulnerability assesses the susceptibility of the receptor (e.g., water table, aquifer, or well) based on the natural properties of the land and subsurface; specific vulnerability also includes properties of a certain contaminant's transport through the subsurface to the receptor. Responses guiding the

level of assessment required in areas of "high" or "low" vulnerability can be developed and implemented at the community or regional level (e.g., for Oliver, see Liggett et al. [2006]; for the Gulf Islands, see Denny et al. [2007]; assessments for Vancouver Island are ongoing).

Additionally, vulnerability assessments can be incorporated within IWRM to bring groundwater protection within the fold of community growth and land use planning. In this way, groundwater vulnerability assessments could be consulted during official community plan reviews and other land use planning processes. The ongoing production and use of vulnerability assessments can contribute significantly to both water management and to heighten awareness of the issue of groundwater protection in British Columbia.

## Acknowledgements

We are grateful to Diana Allen (Simon Fraser University), and Mike Wei and Kevin Ronneseth (BC Ministry of Environment) for their fundamental contributions to vulnerability mapping in British Columbia. ~

## More Information

Smart growth on the ground (Oliver, BC): [www.sgog.bc.ca/content.asp?contentID=156](http://www.sgog.bc.ca/content.asp?contentID=156)

Well protection toolkit: [www.env.gov.bc.ca/wsd/plan\\_protect\\_sustain/groundwater/wells/well\\_protection/wellprotect.html](http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/wells/well_protection/wellprotect.html)

BC Aquifer Classification System: [www.env.gov.bc.ca/wsd/plan\\_protect\\_sustain/groundwater/aquifers/Aq\\_Classification/Aq\\_Class.html](http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/Aq_Classification/Aq_Class.html)

BC Water Resources Atlas: [www.env.gov.bc.ca/wsd/data\\_searches/wrbc/](http://www.env.gov.bc.ca/wsd/data_searches/wrbc/)  
Geological Survey of Canada's Groundwater Research: [http://ess.nrcan.gc.ca/gm-ces/index\\_e.php](http://ess.nrcan.gc.ca/gm-ces/index_e.php)

Vancouver Island vulnerability mapping website: <http://web.viu.ca/groundwater/>

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