

Assessing risk to groundwater quality using an integrated risk framework

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Abstract Source-water protection strategies are ideally focused where the greatest amount of harm reduction can occur. This process of risk management requires an assessment of the spatial variability of risk to water. The assessment methodology presented herein combines aquifer susceptibility with a hazard threat inventory and an analysis of the consequence of contamination to assess the risk to water quality. Aquifer susceptibility combines the intrinsic susceptibility of the physical system with anthropogenic features that locally increase susceptibility. Hazard threats are assessed based on the properties of the chemicals (toxicity and environmental fate), the potential magnitude (extent and quantity of release) and the likelihood of release. The consequence is herein considered as the financial costs of the loss of the resource, including the replacement of a water source and the economic loss where water intensive businesses are lost. A second scenario is included that analyses health issues related to pathogen sources as well as the financial impact to the community where people fall ill and present a financial burden to the public health care system. The risk assessment methodology is applied to the Township of Langley, in southwestern British Columbia, Canada. The results outline the most vulnerable areas as those where susceptible aquifers coexist with potential chemical and biological threats. The risk is greatest where these vulnerable areas coincide with those with the greatest potential for financial loss: within

the capture zones of major municipal production wells and where private wells serve agricultural operations with high annual farm sales.

Keywords Source-water protection · Risk assessment · Groundwater · Aquifer vulnerability · Groundwater contamination · Canada

Introduction

Source-water protection is the first and often most critical part of a multi-barrier approach to drinking water protection (World Health Organization 1993; O'Connor 2002). This strategy involves the identification of water resource vulnerabilities and potential contaminant pathways to select ideal management tools for risk reduction (Ontario Ministry of Environment (MoE) 2004; Ivey et al. 2006). With respect to groundwater, intrinsic aquifer susceptibility mapping (often referred to as aquifer vulnerability mapping; Vrba and Zaporozec 1994) is based on the physical attributes of the subsurface, and is a relative measure of the ease with which a contaminant can enter the subsurface when introduced at surface (Van Stempvoort et al. 1992; Aller et al. 1987). This analysis often considers the physical system at a large scale, ignoring the man-made preferential pathways that increase susceptibility on the small scale, such as wells, mines or other excavations. Although useful planning tools, intrinsic aquifer susceptibility mapping approaches do not consider whether contaminants are actually present or the likelihood of those contaminants causing harm. To better define resource vulnerability, aquifer susceptibility is combined with an inventory and assessment of potential contaminant threats. Andreo et al. (2006), for example, assessed hazards based on three

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factors: the toxicity and mobility of the contaminant, the relative quantity, and the likelihood of contaminant release.

In studies of disaster risk (e.g. earthquakes), the outcome or consequence is an integral part of risk mapping (Birkmann 2006). In a water context, seldom is the consequence of contamination considered. Notable exceptions include Ducci (1999), who used socio-economic value classes with hazard and susceptibility to map risk to groundwater quality. The COST Action 620 concept in Europe has made the consequence of contamination an integral part of groundwater risk assessments for carbonate aquifers (Zwahlen 2004). Ravbar and Goldscheider (2007), for example, assessed the importance of the resource based on the size of the groundwater-reliant population, the quantity of water used, the intensity of agriculture and the ecological importance and irreplaceability of the resource. Others have assessed the economic impact of resource loss based on the market price of agricultural products, as well as the loss of employee salaries (Perles et al. 2009).

The purpose of this study was to develop a risk assessment methodology for source-water protection purposes that is both straightforward and flexible, based on common risk assessment principles. The approach extends previous work in this area by including conduits (as wells) that increase intrinsic susceptibility of the aquifer, by considering a range of potential factors that contribute to financial loss, and by demonstrating a risk assessment method that allows for the integration of various methods of assigning susceptibility, hazards and consequence.

Risk assessment methodology

Introduction

There are several methods in the scientific literature for the assessment of risk and vulnerability (Birkmann 2006). Risk assessment is defined as the “systematic use of available information to determine the likelihood of certain events occurring and the magnitude of their possible consequences” (United Nations International Strategy for Disaster Reduction (UN/ISDR) 2004). This likelihood is based on the presence of human-induced or natural hazards and the vulnerability of the system. Risk is therefore a function of hazard, vulnerability and exposure (Arakida 2006; Asian Disaster Reduction Centre (ADRC) 2005). In most applications of disaster risk assessments, exposure relates to that which is affected, such as people or property (Arakida 2006), and is often quantified by the potential impact (Roberts et al. 2009). The comprehensive mapping of risk as it relates to groundwater resources is most notably completed as part of the Pan-European approach (Zwahlen 2004). The resource’s intrinsic vulnerability is

assessed based on the protective characteristics of the overlying layers (e.g. soil and lithology pollution-attenuating characteristics), the physical setting that leads to a concentration of recharge areas and the amount and intensity of precipitation. The specific attenuation of a contaminant (i.e. the specific vulnerability) is then determined based on characteristics of the contaminant (e.g. vapour pressure, half life, etc.) and the environment (e.g. % organic matter, oxygen supply, etc.). The resulting damage to the resource, both ecological and anthropogenic use, is calculated in terms of economic values. The assessment methodology presented defines the risk of groundwater contamination based on two fundamental components: vulnerability and loss (Eq. 1). Vulnerability is the potential for damage caused by contamination hazards, offset by the natural protection provided by the physical (unaltered or altered) system. Loss is the economic, environmental and/or health consequences associated with the contamination of a groundwater resource.

Risk (due to a specific hazard) is calculated as

$$\text{Risk } (R_H) = \text{vulnerability } (V_H) \times \text{loss } (L). \quad (1)$$

Vulnerability (V_H) includes the susceptibility of the physical system—here the aquifer (aquifer susceptibility, S_A)—and the presence/absence of hazards that may contaminate the resource (hazard threat, T_H), calculated here as

$$\text{Vulnerability } (V_H) = \text{aquifer susceptibility } (S_A) \times \text{hazard threat } (T_H). \quad (2)$$

Aquifer susceptibility is generally stable in time, but can be altered through anthropogenic activities (e.g. the construction of wells, mines and other excavations). These preferential pathways or “conduits” physically remove, or provide bypasses through, the natural protection provided to an aquifer by the overlying geology. The inclusion of such features within susceptibility analyses is uncommon, but conduit assessment has been implemented in some studies (e.g. Ontario MoE 2004). Here, a method is presented for including the impact of man-made conduits, here focused specifically on the example of water wells, on intrinsic aquifer susceptibility. Aquifer susceptibility (S_A) includes both the intrinsic aquifer susceptibility (S_I) and the impact of man-made conduits (C); the potential increase in susceptibility provided by the conduits is based on well characteristics, such as construction, location and densities:

$$\text{Aquifer susceptibility } (S_A) = \text{intrinsic aquifer susceptibility } (S_I) + \text{conduits } (C). \quad (3)$$

Areas of high aquifer susceptibility are seldom at risk without a source of contamination. In this study, the threat

represented by each hazard source is quantified based on factors specific to the chemicals (toxicity and environmental fate), their potential magnitude (onsite quantity and spatial extent), and the probability that each will be released to the environment:

$$\text{Hazard threat } (T_H) = \sum (\text{chemical intensity} \times \text{quantity} \times \text{probability} \times \text{extent}), \tag{4}$$

where

$$\text{Chemical intensity} = (\text{toxicity} + \text{environmental fate})/2; \tag{5}$$

Quantity (Q) = relative volume of a contaminant;

Extent (E) = spatial footprint of area exposed to contamination; and

Probability (P) = likelihood of hazard threat occurrence.

The final component of Eq. 1 is the parameter loss (L), which is the consequence of the resource becoming contaminated. This factor can include a wide breadth of consequences including financial losses or environmental or human health impacts. This methodology builds on similar assessments of loss (Ravbar and Goldscheider 2007; Perles et al. 2009) and focuses on various avenues of financial impacts due to resource contamination. These consequences include the cost to replace a groundwater source (replacement cost); the impact to the local economy where a reasonable replacement cannot be found (economic loss); and the financial burden of health-related issues (healthcare cost). By assessing the impact based on cost, various types of consequences can be included, by relating each to a

common unit: dollars. The overall framework for assessing risk, using the above parameters, is depicted in Fig. 1.

This paper demonstrates two examples of the risk methodology. The first considers the risk of groundwater contamination based on a full suite of potential chemical threats and the financial consequences of pollution. This is referred to as the ‘base case’ scenario. The second risk assessment relates solely to the risk of pathogen-related illness, referred to as the ‘health’ scenario. This scenario considers only pathogen hazard sources and the financial consequences of pathogen-induced illness in end-users.

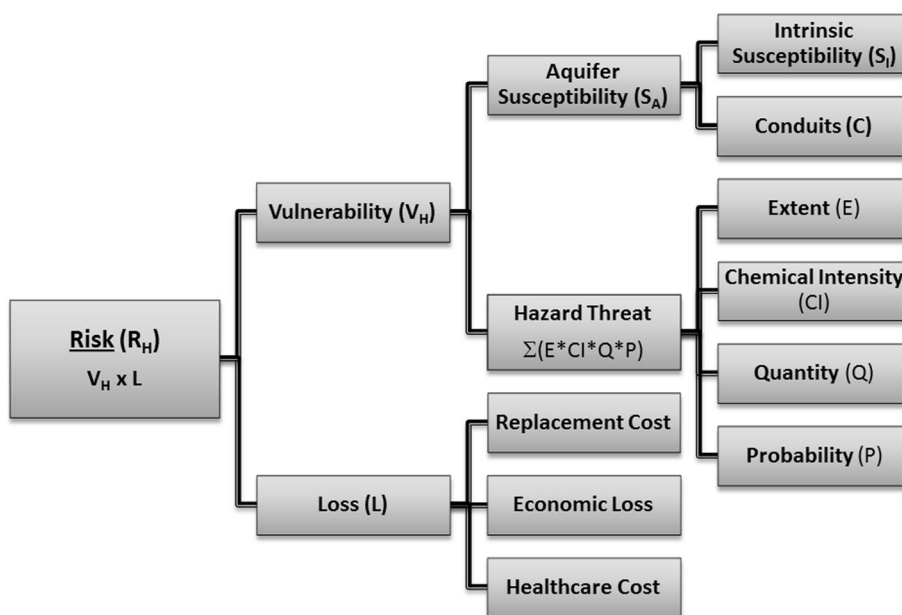
Vulnerability

Aquifer susceptibility

Intrinsic aquifer susceptibility Many intrinsic aquifer susceptibility methodologies are in use today (see review in Vrba and Zaporozec 1994). Some of the more commonly used methods include GOD (Foster 1987), AVI (Van Stempvoort et al. 1992), and DRASTIC (Aller et al. 1987). Specialized methods have been developed for Karst environments (Dorflinger et al. 1999; Goldscheider et al. 2000) and fractured bedrock (Denny et al. 2007). Because each method determines susceptibility differently, the result of one method is not directly comparable to another. In some cases, different methods have shown strong divergence in susceptibility (Gogu and Dassargues 2000; Neukum and Hotzl 2007).

The risk methodology described herein is designed to be transferrable to any region. Therefore, no single susceptibility assessment method is preferred, provided the method used adequately defines intrinsic susceptibility for the

Fig. 1 Risk assessment framework



region. Where it is not possible to complete a susceptibility assessment using a defined method, it is possible to gauge relative susceptibility in a general way using available data. For example, a soil map in combination with a map of topography can be used to roughly outline areas of high (permeable soils, low slope) and low (impermeable soils, high slope) intrinsic susceptibility. Conversely, where advanced methods are possible (e.g. time of travel derived from numerical models), these results can be similarly utilized. Regardless of the method of assessing intrinsic susceptibility, the results need only be reclassified using a scale of 1–10 to use it in the risk methodology.

Conduits Boreholes into the subsurface, including geotechnical and water wells, provide a pathway through which a contaminant can move directly into a deep aquifer (Ontario MoE 2004), increasing the intrinsic susceptibility of an aquifer at the scale of the wellhead (Fig. 2). The greatest potential source of conduits within the study area is the 5,000–10,000 wells that are believed to exist; wells are therefore the focus of the assessment of conduits but are only one potential example. The probability that the well will act as a conduit will depend on the well construction and location characteristics. For example, the presence of an effective surface seal (a low-permeability material installed to seal a well's annular space; Fig. 3) can have an impact on the likelihood the well's annular space will act as a conduit for contamination. Contaminants may also travel into an aquifer within the well itself if a secure well cap is not installed.

Where a well is placed within a topographic depression (large scale), surface runoff carrying contaminants is more likely to collect near the wellhead, increasing the chances of downward migration through an annular space or uncapped well (Fig. 2). At the local (small) scale, if the ground around a well is graded away from the well casing

(Fig. 3), contaminants will not pond around the wellhead. These large- and small-scale slopes around the well are important features in determining the likelihood that a contaminant will enter the groundwater system via the well. Well placement can be determined using onsite knowledge (most ideal) or using available contour maps or digital elevation models (DEMs). The degree to which a wellhead is properly graded requires onsite knowledge of the well.

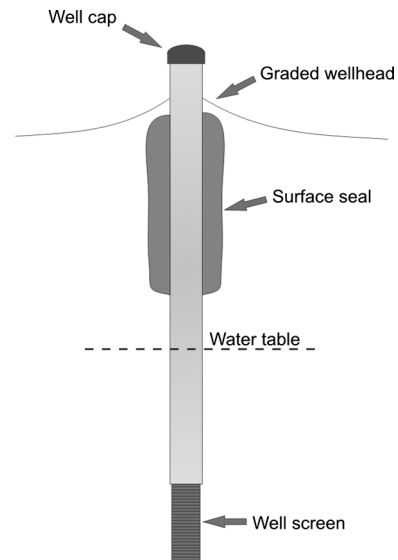
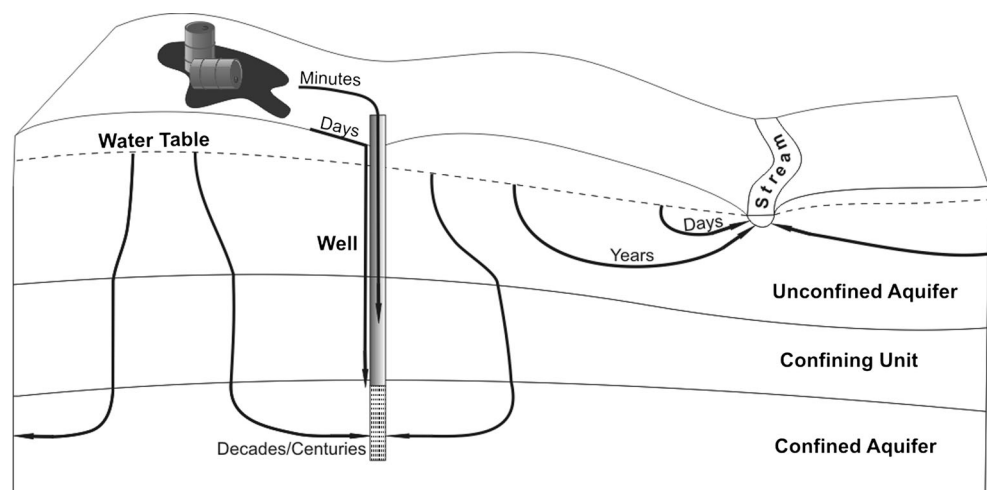


Fig. 3 A low-permeability material (sealant) is installed around the well casing, near the surface, forming a surface seal. This seal prevents any contaminants at the surface from using the outside of the well casing as a preferential vertical pathway to the aquifer at depth. A proper well cap prevents contaminants from entering the well casing directly. Grading the land surface away from the wellhead prevents surface contaminants from collecting around the casing and making their way into any annular space that may exist around the well casing

Fig. 2 A well can act as a conduit, allowing surface contaminants to enter a deep aquifer, either directly inside the well or along an annular space outside the well casing



In addition, as properties hook up to municipal water, or wells are replaced, unused wells are often left abandoned. Over time, these wells fall into disrepair and are often ‘lost’ under vegetation, becoming a risk to the aquifer as a conduit. Table 1 lists the characteristics and scores used to assess wells as potential conduit threats.

Overall aquifer susceptibility To combine conduits with intrinsic aquifer susceptibility (Eq. 3), the study area is converted into a raster grid (50 × 50 m). Each grid cell is assigned a conduit threat value based on the well(s) it contains (Table 2); where more than one well is located within a single grid cell, the cell is assigned a cumulative value of the conduit scores. The overall score for each raster cell is then classified using a scale of 0 (no wells) to 5, as per Table 2. The values for conduits (0–5) and intrinsic susceptibility (1–10) are added using raster addition in the GIS (Eq. 3) and reclassified using a 1–10 scale.

Table 1 Rating scheme for assessing the level of conduit threat provided by a well

Construction category	Score	Characteristic
Presence of a well	0	No well present
	1	Well is present
Effective surface seal	0	Good seal installed
	1	Adequate seal installed but length or width is not ideal
	2	Adequate seal likely installed
Well cap/cover	3	Adequate seal likely not installed
	0	Adequate cap installed
	1	Adequate cap likely installed
Likelihood of ponding around the wellhead	2	Adequate cap not likely installed
	0	Ponding is unlikely
	1	Ponding is probable
Abandoned	2	Ponding is highly likely
	0	Well in use or closed
	2	Well likely abandoned and in disrepair

Table 2 The cumulative conduits scores (Table 1) are used to assign a conduit threat value to each raster cell

Cumulative conduit score	Conduit threat value
0	0
1–5	1
6–11	2
12–19	3
20–29	4
30 or more	5

Hazard threat

Land use contaminant inventory A detailed onsite investigation throughout the study area is the most ideal form of chemical hazard assessment. However, such a task is extremely time consuming and is seldom done. To make the inventory process more manageable, it is preferable to use information that is readily available. Land use data, for example, can be used to map potential hazards, based on the typical chemical hazards found on a particular land use. Assumptions made during the mapping process can be confirmed through site investigations or using aerial photographs. Other useful data include permits or licenses for operations of interest, such as landfills, gas stations or hazardous waste storage facilities.

The current study creates an inventory of chemical hazards based on land use, classified using the North American Industry Classification System (NAICS). These data are used to populate each parcel with the typical contaminants found on the land use type (US Environmental Protection Agency 2004). The hazard is then analysed further to determine the relative threat. Each contaminant is assigned a toxicity and environmental fate (Ontario MoE 2004) and a chemical intensity (CI) is calculated using Eq. 5. Depending on the level of knowledge available, the contaminants can be assessed by group (e.g. agricultural waste) or by individual contaminant (e.g. nitrate). The quantity (*Q*) stored or used on each parcel must be estimated (scale of 1–10) using available records or by persons with local knowledge of common practices. Further, the probability of release (*P*) to the environment must be rated (1–10). This probability is based on several factors, such as the level of spill response in the area, legislative requirements of storage and use of contaminants, as well as local or industry best management practices (BMPs). Similarly, quantity and probability can be generalized by operation type (e.g. dairy farms) or by individual operations (e.g. Frank’s Dairy Farm). The final variable in Eq. 4 is the extent (*E*) or spatial footprint of potential contamination. This is expressed as a percentage of the parcel (e.g. fertilizer application over 80 % of the parcel is assigned a level of 8). Where the extent is expected to be a small percentage of parcel area, it may be preferred to treat the hazard as a point source.

Point sources With point sources, such as fuel storage, the hazard threat methodology is nearly identical to diffuse sources. Instead of applying the hazard threat to a relative extent of the entire parcel (e.g. 80 % = 8/10), the assumed area of release is mapped separately from the parcel, and an extent rating of 10 is applied to the area that defines the point source. The quantity, chemical intensity and probability are then assessed as described above. To integrate the

two, the point source hazard scores are simply added to the diffuse scores over the land base where the two coincide.

Overall hazard threat The assessment of individual hazards is a combination of chemical quantity, intensity, extent and probability of release (Fig. 1). Each of these variables is assessed on a 1–10 scale for each hazard and then each parcel is assessed a cumulative total of the hazards present, as per Eq. 4. The final hazard threat is based on the cumulative total of each parcel, reclassified to a 1–10 scale. This is accomplished with greater ease using a relational database outside of a GIS; a database allows for timely re-assessment of hazard scores as new information is received or conditions (e.g. legislation, BMP's) change.

Vulnerability

Following the assessment of aquifer susceptibility and hazard threats, vulnerability is calculated using Eq. 2 and the results reclassified using a 1–10 scale.

Loss

The contamination of groundwater has environmental, human health and economic consequences. The magnitude of these consequences is difficult to quantify due to the wide variability in potential contaminant type, soil and rock properties, hydrology and socioeconomic conditions. In order to assess the consequence of a spill, a reasonable approach is to consider the implications of a complete loss of the resource. Although a simplification, this method allows users to examine the relative impacts of the loss of the resource across the study area.

One or more indicators for the potential loss due to contamination can be used for this assessment. The choice of indicators should be based on the values of the community, but will ultimately be limited by data availability and resources. A simple method may be to assess the number of people affected by contamination. The present study looks at financial implications, focusing on three major areas: the replacement cost of potable water, the economic loss incurred following the closure of a water intensive business (e.g. agriculture), and the healthcare costs incurred for water-related illness. These financial loss assessments are but a few examples of a wide range of possible loss indicators that could be used.

Replacement cost

With the contamination of a potable water supply, a new source must be found (assuming the cost of treatment is too high). In areas with favourable geology, deeper aquifers may be accessed if shallower units become contaminated. Where

deeper groundwater does not exist, municipal supply may be available. If supply is not located nearby, the costs to land-owners for water main extension are often too high to justify. Other potential options include surface water sources, bulk water delivery, onsite filtration or rainwater harvesting. Each parcel is assigned a loss based on the cost of the cheapest available alternative water source.

Economic loss

In some cases, the loss of a well may have economic impacts that stretch beyond a single homeowner. For water intensive businesses, such as agriculture, it may be difficult or even impossible to replace its groundwater source. Often, even if municipal supply is available the volumes required are too large for the municipal system to provide. If surface water sources are not available nearby, the business owner may have no choice but to shut down. This situation may have complex and far reaching impacts on the local economy, depending on the size and nature of the business. To simplify the assessment, each parcel is assigned an economic loss based on the annual revenue generated by the business.

Healthcare cost

Water-borne illnesses represent a serious threat to the well-being of groundwater users (Uhlmann 2009). The impact of water-borne illness is difficult to quantify as it may vary by pathogen type (e.g. *E.Coli* vs. *Cryptosporidium*), level of water treatment, frequency of monitoring, and vulnerabilities of the population affected (e.g. elderly and infants). Besides the suffering of the affected persons, there is a financial implication to the individual, community and region related to the loss of wages, travel costs and burdens on the medical system. Wells affected by pathogen-related hazards are assessed a cost based on the number of people served and an average cost per case of gastrointestinal illness of \$1,343 (Henson et al. 2008). A well is considered to be affected if a pathogen source (e.g. manure spreading agriculture or septic system) is located within the 1-year capture zone of the well (Goss and Richards 2008).

Overall risk

The calculation of overall risk is a simple combination of the vulnerability assessment with the loss assessment via multiplication, as shown in Fig. 1.

Study area

The study area used to test this methodology is the Township of Langley (the Township), located 45 km east

of the City of Vancouver, in south-western British Columbia (BC) (Fig. 4). Historically a highly productive agricultural community, the Township is struggling with urban growth; the population is estimated to grow from 100,000 at present, to 165,000 over the next 15 years. Currently, much of the rural area is serviced by approximately 7,600 private wells; the more urbanized areas are served by the municipal system. Nearly all agricultural activity is sustained through private wells and accounts for over \$200 million in annual farm sales (Statistics Canada 2007). The municipal system relies on 18 production wells as well as surface water from the Greater Vancouver Water District (GVWD; water is sourced from surface watersheds in the mountains to the north of the City of Vancouver—remote from the study area. Water is piped to the Township). Overall, approximately 80 % of residents use groundwater for their water needs (Inter-Agency Planning Team 2009); therefore, the social and economic health of the Township is highly linked to groundwater. Nitrates sourced from agricultural fertilizer and septic systems are known to negatively impact groundwater quality throughout the Township (Carmichael et al. 1995; Li and Schreier 2004).

The Fraser Lowlands comprise a complex mix of glacial drift deposits (Clague 1994). The geology in the Township is a complex mix of Quaternary tills, ice-contact deposits, glaciomarine deposits, and glaciofluvial sands and gravels (Golder Associates Ltd 2005). These sediments exist down to bedrock at depths of 200–500 m. Recent modelling work

delineated 45 permeable units within the Township (Golder Associates Ltd 2004).

Results and discussion

Vulnerability

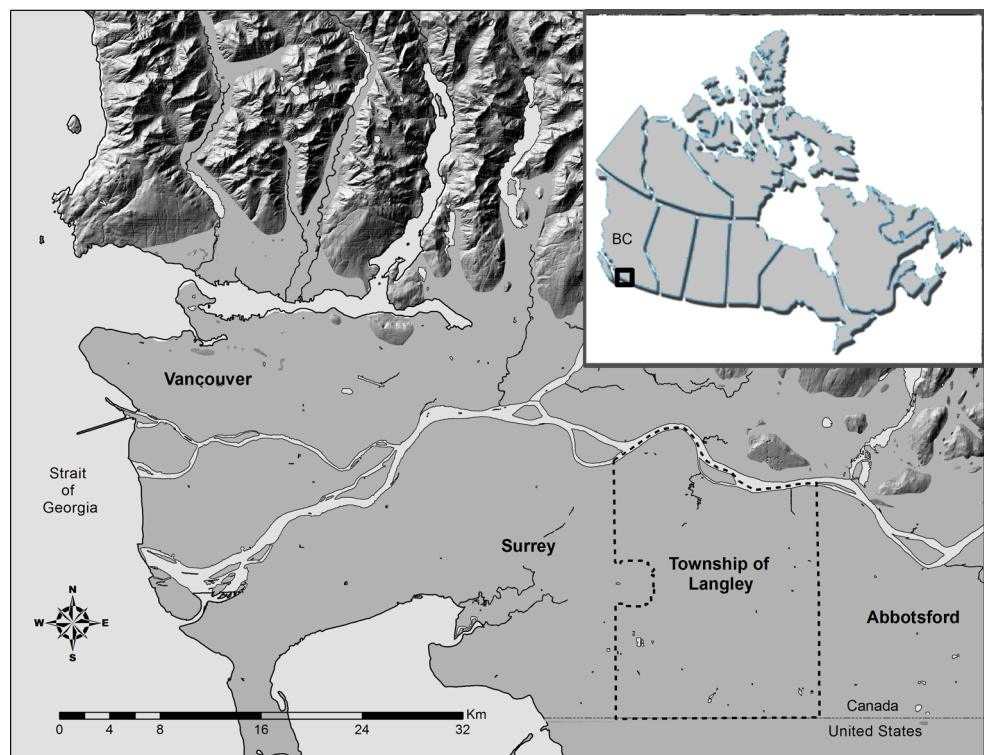
Aquifer susceptibility

Intrinsic aquifer susceptibility Recently, Golder Associates Ltd (2005) completed a Township-wide intrinsic aquifer susceptibility mapping project, using the Aquifer Vulnerability Index method (AVI; Van Stempvoort et al. 1992). AVI requires only two parameters: the thickness and hydraulic conductivity of each layer above the aquifer. The intrinsic aquifer susceptibility is calculated as the sum of the hydraulic resistance, c , for each layer:

$$c = \sum (d/K), \tag{6}$$

where d = layer thickness [length], and K = hydraulic conductivity [length]/[time]. The hydraulic resistance is calculated on a well by well basis, and a map is generated by contouring the results. The AVI method calculates the hydraulic resistance of the shallowest aquifer at any one location. Therefore, in areas where unconfined aquifers exist, any confined units beneath are ignored. This is thought reasonable as the most readily accessible units (i.e. the shallowest) will be used preferentially.

Fig. 4 Township of Langley (dotted outline) in the Lower Fraser Valley, British Columbia



Well records from the BC Ministry of Environment's (BC MoE) database, WELLS, were used as sources for lithology data. Hydraulic conductivity values were approximated using values from the literature (Freeze and Cherry 1979). The results of the AVI method (Fig. 5a) show high susceptibility in areas where shallow unconfined units exist and low susceptibility where the shallowest aquifers are confined. Previous AVI studies in the Fraser Valley have shown a strong correlation between highly susceptible areas and high nitrate values (Ronneseeth et al. 1995), suggesting that this vulnerability method is well suited for the physiographic setting.

Conduits A list of wells within the Township was downloaded from the provincial WELLS database. These well records are submitted voluntarily by local well drillers and are therefore not considered to be a complete record of all wells within the Township.

The wells were assessed according to Table 1. A lack of detailed information in the well records required assumptions to be made based on regulatory requirements and common installation techniques. In BC, the installation of an effective surface seal and well cap and proper wellhead grading were only mandated as of 2005. Where information on well construction was omitted from the database,

the well age was used as an indicator of the probability of installation of these components. The reported installation method or type of well was also used to infer well characteristics. Due to the difficulty of placing an effective surface seal on a dug well, a seal is not commonly installed. Drilled wells, in contrast, are constructed with equipment that allows for the installation of a seal with greater ease. Of the 5,790 well records in the Township, only 124 included details about the surface seal; the likelihood of installation of an effective seal was based on the well construction date and the well type. Industry practice prior to 2005 was to install a seal with a drilled well, but this was less common with dug wells. Based on local knowledge of practices, nearly all drilled wells were constructed with a well cap, regardless of drilling date (BC MoE personal communication); many dug wells were completed with a well cover, but most of these are not suitable as watertight caps.

Contaminants released at surface in areas of steep slopes will tend to runoff (Aller et al. 1987); therefore, wells located on flat terrain are more likely to have surface waters pond near the wellhead. To assess this impact, a raster of slope was created from a DEM of the study area using ArcGIS 9.3 (ESRI 2008). Areas of slope $<5^\circ$ were

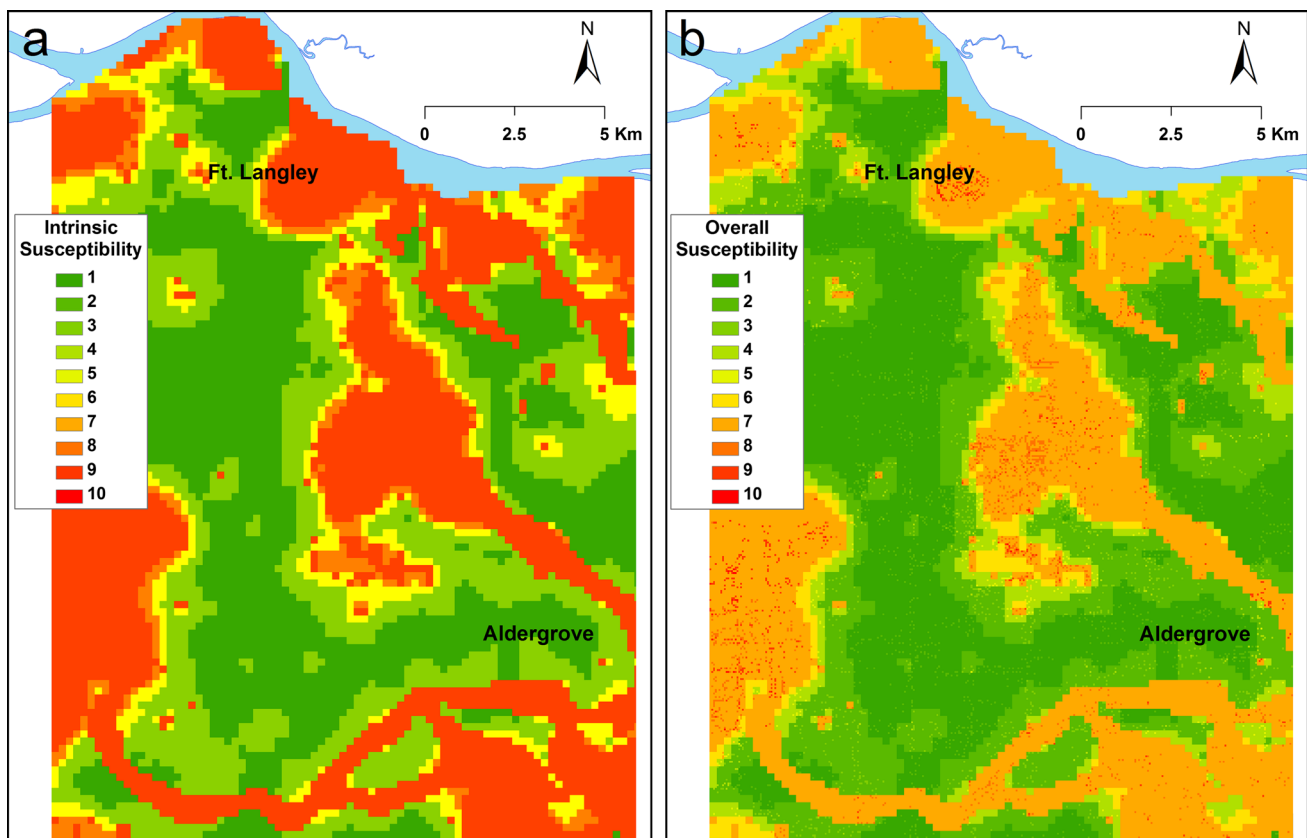


Fig. 5 Intrinsic aquifer vulnerability (a) vs. overall aquifer susceptibility (b). Intrinsic aquifer susceptibility originally mapped by Golder Associates Ltd (2005)

deemed more favourable to surface ponding. Similarly, the grading of the ground immediately adjacent to the well can prevent ponding next to the wellhead. This basic means of wellhead protection is mandated for wells constructed after 2005.

Over the past 20 years, the extension of the municipal water supply mains has allowed many Township residents to connect to the municipal system. Wells no longer in use for drinking water are seldom closed following municipal connection. Wells located on parcels served by municipal water and not involved with agricultural activity were assumed to be abandoned, unless a well closure report was available. A total of 995 wells were identified within the Township as being abandoned.

Each well was assigned a conduit score based on Table 1; the assumptions used to assess wells in the study area are summarized in Table 3. The use of a 50-m grid likely overestimates the surface catchment of a conduit;

however, the size is considered necessary to allow for analysis on such a large scale and is considered a reasonable distance for a contaminant to travel laterally at the ground surface, towards a well. As discussed above, there are a large number of wells believed to exist within the study area, yet specific details about well construction and location are often lacking. Although several simplifying assumptions are made, the analysis is considered reasonable given the authors’ familiarity with local well construction and maintenance practices. Despite the method’s limitations, it is thought to be useful as an example for assessing the impact of man-made features on the system’s intrinsic susceptibility. It should be noted that where data are sufficiently lacking, the analysis of conduits can simply be omitted in the overall risk assessment.

Overall aquifer susceptibility The combination of intrinsic aquifer susceptibility with conduits maintains high

Table 3 Assessment of conduit scores

Construction category	Score	Assumption	Justification/distinction	Basis of decision
Presence of a well	0	No well present	Natural susceptibility is not affected	Absence of a well
	1	Well is present	Natural susceptibility is increased	Presence of a well
Effective surface seal	0	Good seal installed	Well construction report specifies adequate length and width of seal	Well record specifies at least 15 feet of sealant, 1 inch thick
	1	Adequate seal installed but length or width is not ideal	Well construction report specifies the length and width of sealant but values are below standards; surface seal required to have been installed	Well record specifies <15 feet of sealant; well was drilled after 2005
	2	Adequate seal likely installed	Well construction report does not include surface seal details but industry practice generally includes does include seal installation	Well was drilled before 2005
	3	Adequate seal likely not installed	Well construction report does not include surface seal details and industry practice generally does not include seal installation	Well was dug prior to 2005
Well cap/cover	0	Adequate cap installed	Well cap required by legislation	Well was constructed after 2005
	1	Adequate cap likely installed	Well cap not required by legislation but industry practice includes cap installation	Well was drilled prior to 2005
	2	Adequate cap not likely installed	Well cap not required by legislation and industry practice does not include cap installation	Well was dug prior to 2005
Likelihood of ponding around the wellhead	0	Ponding is unlikely	Well construction legislation requires wellhead grading and well location is favourable	Well constructed after 2005 and slope is >5°
	1	Ponding is probable	Well unlikely to have wellhead grading OR well location is unfavourable	Well constructed prior to 2005 OR slope is <5°
	2	Ponding is highly likely	Well unlikely to have wellhead grading AND well location is unfavourable	Well constructed prior to 2005 AND slope is <5°
Abandoned	0	Well in use or is closed	Well is likely to be properly maintained	Well located on a property without municipal water OR agricultural activity OR well closure report is available
	2	Well likely abandoned and in disrepair	Well believed to be no longer in use	Property has municipal water AND no agricultural activity ongoing

aquifer susceptibility scores in areas above shallow, unconfined aquifers and increases the susceptibility of confined aquifers (normally of low susceptibility) in areas of high well density. At the scale of Fig. 5b, it is difficult to assess this change, but 4.3 % of the areas with an intrinsic susceptibility less than 4 were increased one or two overall susceptibility levels with the addition of conduits. Areas of high intrinsic susceptibility were ranked as marginally (to a maximum of 20 %) more susceptible by a high density of wells, relative to natural conditions.

The results likely underestimate the impact of conduits: of 7,600 parcels believed to be currently served by a private well in the Township, only 4,200 parcels show a well in the WELLS database. It is likely that even more unregistered abandoned wells are located on properties now served by municipal services.

Hazard threat

Land use contaminant inventory Using land use data available through the BC Assessment authority and the BC Ministry of Agriculture, a contaminant inventory was completed. Using a custom Microsoft Access database, the quantity and probability of release were assessed by chemical group for each land use type. These were combined with the chemical intensity and extent using Eq. 4, to calculate a hazard threat score for each parcel.

Point sources A known source of groundwater contamination within the Township is biowaste from onsite sewage systems (a.k.a. septic systems; Wernick et al. 1998). These systems serve the sewage disposal needs of parcels outside the range of municipal services. In BC, unless it serves a large population, a septic system is unregulated; the location and condition of these systems are largely unknown. The Township maintains records of the parcels serviced by the municipal sewage system, but not private systems. Parcels not on the municipal system were assumed to be on a private system, unless sewage was not necessary (e.g. vacant lots). Extensive aerial photograph interpretation was required to determine whether a parcel was being used for its designated purpose. The location of each system was assumed to be near the largest structure on each property.

In BC, regular maintenance of septic systems is not required by law. The age of the system was used to infer a likelihood of failure. Each system was assigned a value on a 1–10 scale, which represents the probability of release (Table 4).

The quantity of contaminant release is related to the number of people using the system; land use was used to infer this number (Table 5).

Table 4 BC Assessment Authority (BCAA) year built data were used to infer a likelihood of failure (and thus release of excess biowaste)

BCAA year built value	Probability value
Post-2005	1
1998–2004	4
1978–1997	7
Pre-1978	9

Table 5 Ranking system for assessing the quantity related to septic system hazards

Quantity	Characteristic of rank
2	<6 people, 10 h/day—e.g. small park outhouse
3	<6 people, 24 h/day—e.g. single family dwelling
5	<50 people, 10 h/day—e.g. small businesses
7	<50 people, 24 h/day—e.g. small care facility
8	>50 people, 10 h/day—e.g. large business office, golf course
10	>50 people, 24 h/day—e.g. mobile home park, hospital

The chemical intensity was calculated using the same techniques as for diffuse hazard sources; contaminants of concern related to human waste include nitrite and nitrate. The extent of contaminant release is given a rating of 10, over the inferred area of the septic field. A threat value for each septic system was assessed over this smaller area, using Eq. 4.

Overall threat Following the independent calculations of hazard threats from point and diffuse sources, the scores were combined using ArcGIS and reclassified using a 1–10 scale (Fig. 6a). Hazard values of 9 and 10 were reserved for landfills, automotive service stations and garages as well as some other light industry. Much of the rural area was ranked between 3 and 8, with relatively high scores dominated by high manure producers (e.g. poultry) and manure and pesticide spreaders (e.g. small fruits); the highest values were achieved where these agricultural operations were also serviced by private onsite sewage disposal systems. The lower threats were predominantly rural homesteads (score of 2–3) and small urban homes (score of 1).

To address the risk of pathogen-related health issues (i.e. the Health Scenario), a subset of the full threat inventory was created (Fig. 6b). This inventory includes agricultural operations where manure is assumed to be used as fertilizer as well as private onsite sewage systems. These pathogen threats were assessed using a simplified threat assessment whereby chemical intensity was removed due to a lack of data on toxicity and environmental fate related to individual pathogens.

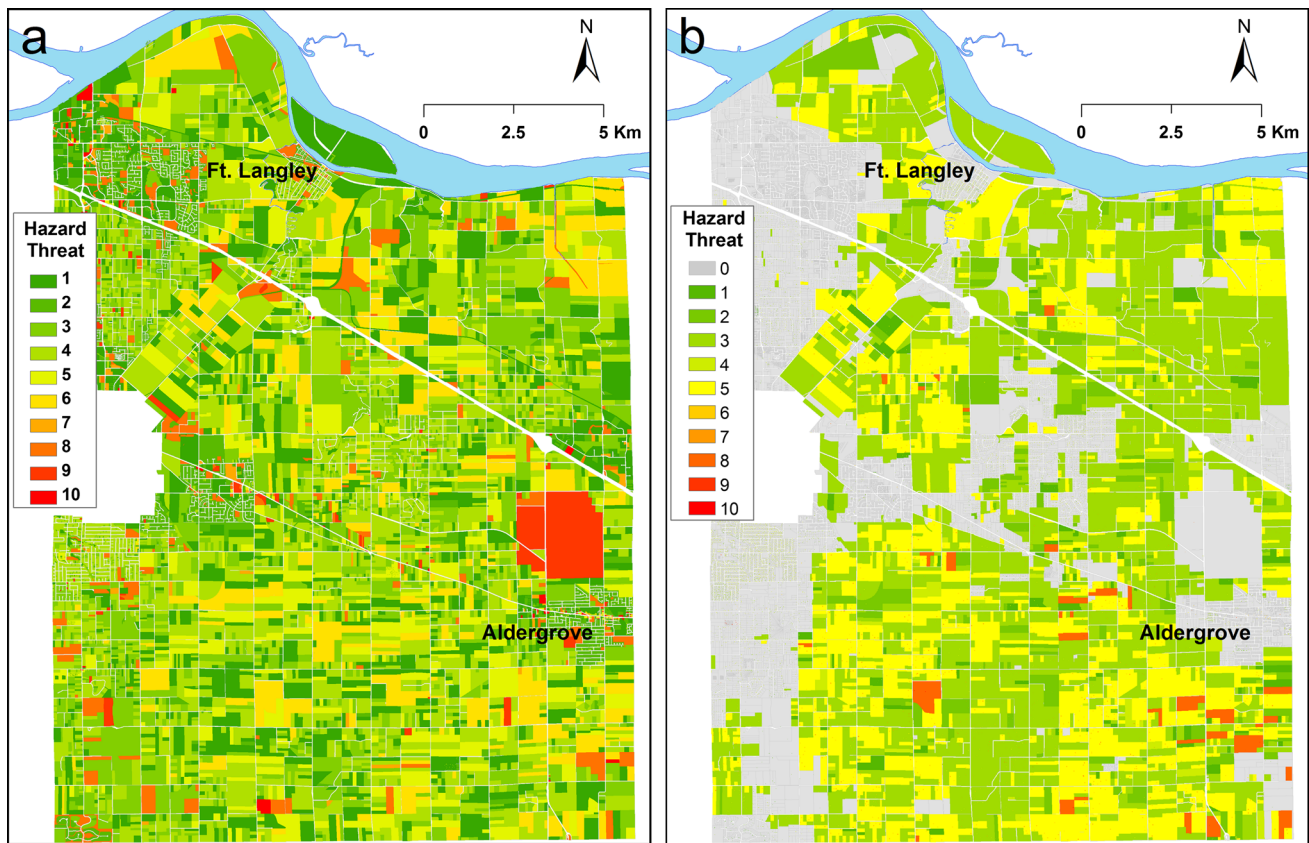


Fig. 6 Hazard threat assessment for the base case scenario (a) and hazards from pathogen sources only (b)

The hazard threat assessment process is highly variable. Besides the chemical intensity variable, which is independent of local conditions, the threat assessment inputs rely heavily on extensive data or local expertise. The current assessment was completed by one researcher with generalized local knowledge. The confidence of the absolute results is thus quite low; however, the relative threat levels by land use type are thought to be maintained. This portion of the assessment would benefit from input from various stakeholders and local experts. In some cases, there may be other data available to better assess the factors of extent, quantity and probability. Government records may include the locations and quantities of stored contaminants, assisting with the assessment of extent and quantity. Further, spill records may be used to better establish levels of probability of release.

Vulnerability

The overall vulnerability assessment combines aquifer susceptibility with hazard threat, as per Eq. 2. This was completed for both the base case (full hazard inventory; Fig. 7a) and the health scenario (pathogen sources only; Fig. 7b).

Loss

Three major aspects of financial loss from contamination are addressed: those related to water source replacement, to economic losses where business can no longer operate, and to losses incurred by the community and individuals where people become sick. The “base case” risk assessment scenario includes the costs related to water source replacement and potential economic losses. This assessment is treated separately from the second risk example, which is related to healthcare cost. This latter aspect of loss is based on pathogen hazards only, which are a subset of the overall hazard inventory.

In order to assign a loss value, hazards need to be linked to the specific well(s) that will be affected; three methods were used to demonstrate a range of potential data availability. These methods include (1) parcel basis where it is assumed that contaminants released on a parcel will contaminate the water supply of that parcel—used to assess private well replacement cost and economic loss; (2) simple analytical methods for determining capture zones—used to assess private well healthcare costs; and (3) numerical methods for determining capture zones—used to assess municipal system potable water replacement and healthcare costs.

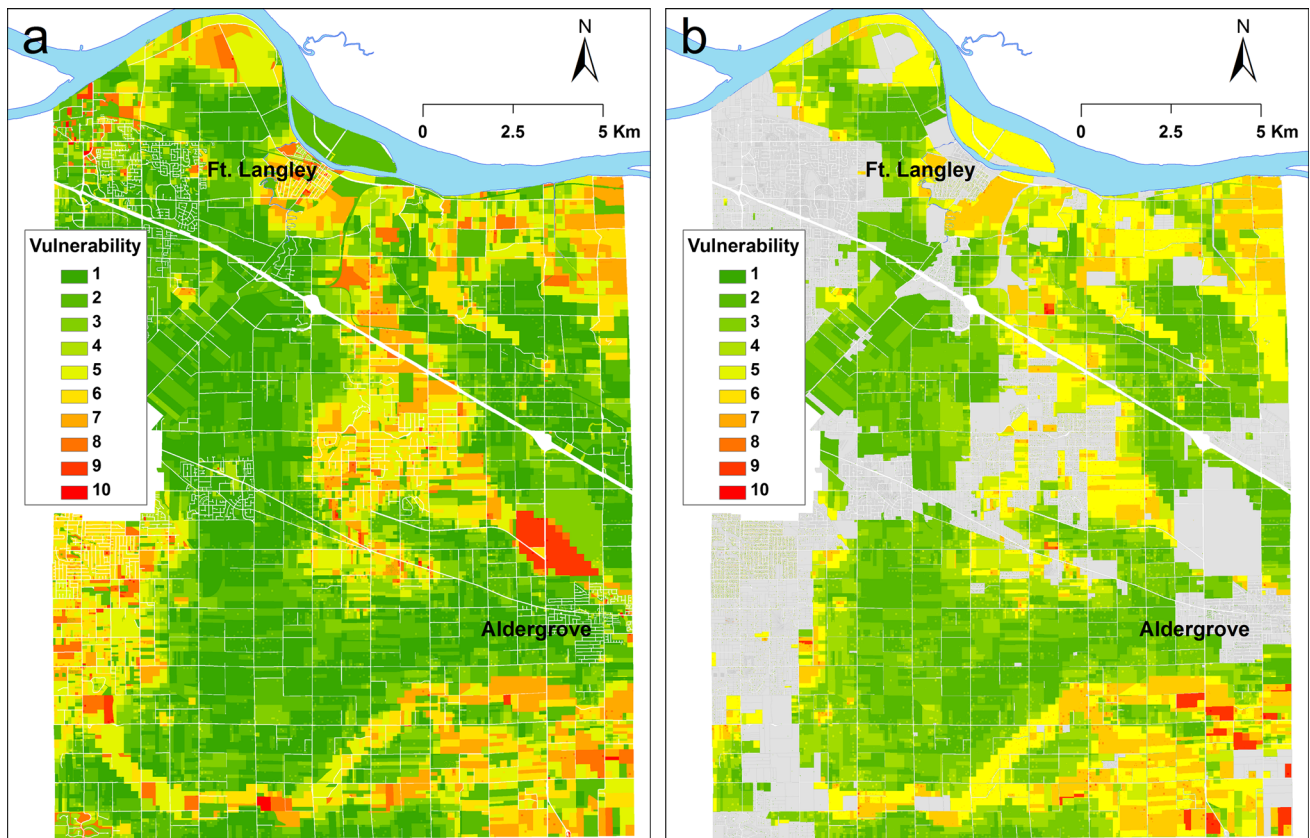


Fig. 7 Final vulnerability assessment results: base case scenario (a) and health scenario (b). Grey areas in b relate to built up areas with no septic systems or agricultural land use

Replacement cost

The contamination of a private well would leave the users without potable water. The landowners may have the option of hooking up to municipal water supply where available, drilling a deeper well if the geology allows, or will need to import water or invest in another expensive long-term solution such as water treatment. Similar financial consequences could impact the municipal water utility; the Township extracts over 8 million m³ of groundwater per year (Golder Associates Ltd 2005) at significant cost savings over purchasing water from the GVWD, a regional water purveyor.

In most cases, upon contamination of a private well, the cheapest available option is to install a new well into a deeper aquifer. This option does not take into consideration the quality of deeper groundwater; arsenic is one issue known to exist in confined aquifers in the region (Cavalcanti de Albuquerque 2011). This scenario would represent a onetime cost for the drilling and equipping of the new well. The cost of a new well will vary depending on the depth drilled; however, to simplify the assessment, a reasonable cost of \$15,000 was associated with the installation of a new domestic water well; an irrigation well, typically

constructed with a larger diameter to accommodate increased flow rates, was assessed a \$20,000 cost. Unfortunately, fewer than 25 % of Langley properties that rely on shallow groundwater are located in areas where deeper aquifers are known to exist. Where deeper aquifers do not exist, a second option is to connect to municipal water. The Township's network of municipal lines is limited in the rural areas that are dependent on private wells. The cost to extend a municipal water line is estimated at \$750 per metre (Inter-Agency Planning Team 2009); a conservative estimate of \$1,000 per metre was used. For a cost greater than \$30,000, it is believed that many residents would seek alternative sources; therefore, water mains' extension beyond 30 m was not considered. All other parcels were assessed a \$50,000 cost to estimate the long-term cost to purchase and operate an alternative water source (e.g. rainwater harvesting, onsite filtration, etc.), but also to emphasize the lack of available alternatives in many areas of the Township. The results are shown in Fig. 8a.

The Township's water utility uses 18 production wells to supplement surface water that is purchased from the GVWD. Extracted groundwater is estimated to be three times more cost effective than purchasing water from the GVWD, saving the Township over \$2 million per year

(\$0.24/m³; Inter-Agency Planning Team 2009). Contaminant release within the capture zone of a Township well would require the purchase of more costly water from the GVWD. Thus, each Township production well was assigned a dollar value based on its extraction volume and a rate of savings of \$0.24 per m³. Therefore, each parcel within the modelled 5-year capture zone (Golder Associates Ltd 2005) was assigned a loss value based on the production well value (Fig. 8b). The 5-year capture zone was used to remain somewhat conservative without overly emphasizing the impact to the water utility (i.e. vs. using a 20-year capture zone).

Economic loss

Without a viable water source, agriculture, which represents over \$200 million in annual economic revenue (Statistics Canada 2007) within the Township, would not be sustainable. The majority of water used for agriculture within the Township is sourced from groundwater. Municipal water supply does not have the capacity to sustain large farming operations. A new, deeper well would provide a relatively inexpensive alternative for a farm, where the geology allows. However, where this is not possible, very few options remain. A surface water source (such as a

stream) may exist, but it is considered unlikely that one would be found nearby that is not already fully allocated. Without a viable source, the farm would no longer be able to operate, creating a financial impact to the local economy.

To simplify the assessment, each parcel was assigned an economic loss on the annual revenue generated by the business. Detailed farm-by-farm income was not available; average annual revenue (\$/acre) for various agricultural types was obtained from readily available data for the US (US Census Bureau 2007). Using these data, each parcel in the Township was assigned an estimated annual farm sales value. The result of this estimate, a total annual Township-wide farm sale of \$27.5 million, is well below the total reported sales of over \$200 million. A likely cause of this discrepancy is the intensive nature of agriculture within the Lower Fraser Valley. In order to ensure the economic loss values better reflect actual farms sales, the estimates were increased proportional to agricultural type to match the total Township output (Fig. 9).

This analysis assumes that contamination on a parcel will contaminate (eventually) any wells located on that property. In many cases, especially where the wells onsite draw from confined aquifers, this assumption may not be met.

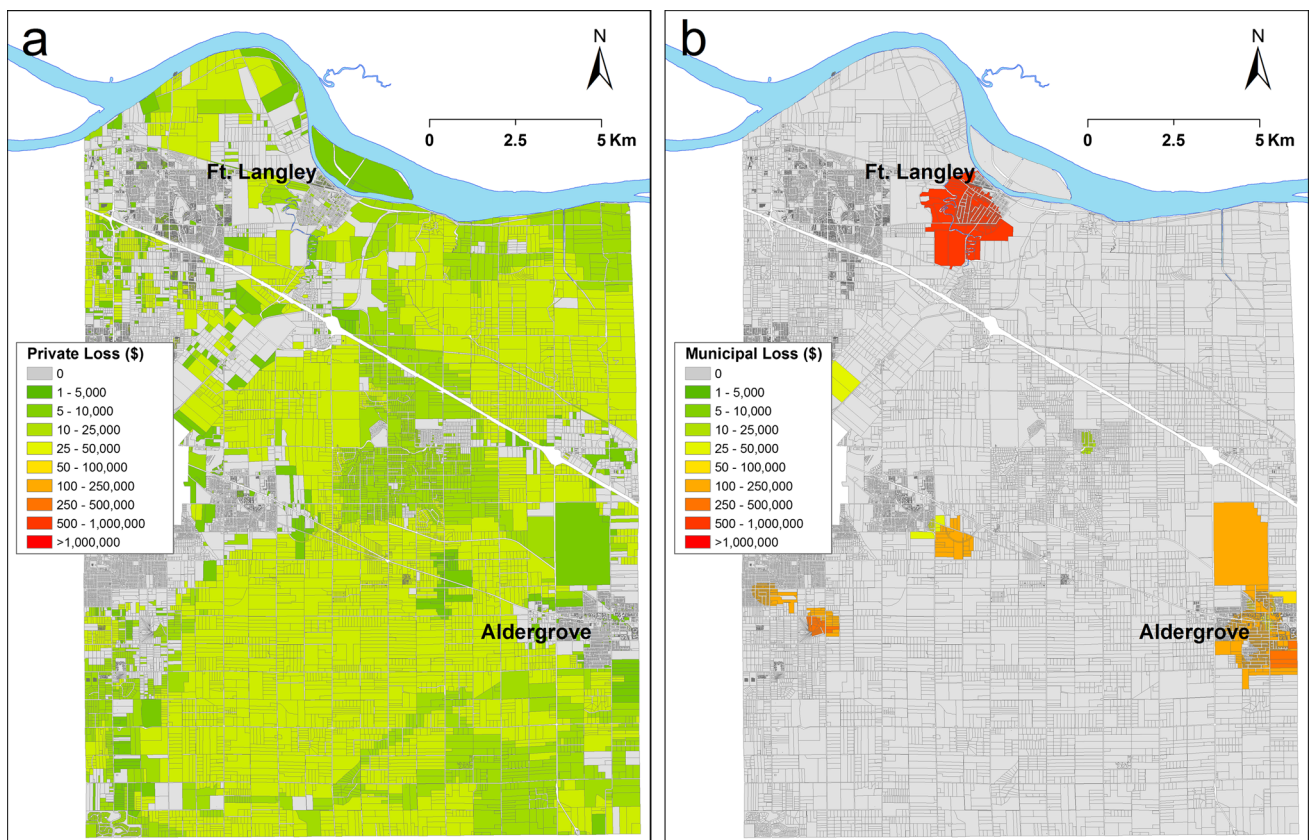


Fig. 8 Replacement costs (\$) to private well owners (a) and to the municipal water utility (b)

The cumulative financial loss thus far for the base case was calculated, and the results classified using a 1–10 scale, based on the dollar value classes presented in Table 6. The results (Fig. 10) stress the relative importance of a small number of high output agricultural operations, as well as areas within municipal production well capture zones.

Costs not considered include that of remediation of groundwater; costs of this nature would be in addition to

loss values calculated here but are difficult to quantify with any level of confidence. A more detailed assessment of the costs of options not included here (e.g. rainwater harvesting, water filtration) would further refine the cost analysis.

Healthcare cost

In order to assess loss related to health complications, a simplifying assumption was made. Each person drinking water from a well that is affected by pathogen-related hazards is assumed to become impacted, and that impact will be fairly minor (so called ‘average’ case: <4 days loss of work plus medical costs). This simplification may underestimate the overall impact where loss of life is involved; however, it does not preclude future analysis involving an assessment of susceptible populations (e.g. the elderly). Wells likely to be affected are those where a pathogen-related hazard (manure spreading agriculture and septic systems) is within the 1-year travel time capture zone. One-year travel time was used as most pathogens cannot survive for extended periods of time in the sub-surface (Goss and Richards 2008). Capture zones were available for the municipal wells (Golder Associates Ltd 2005) but not for the other 7,000+ private and community wells. Capture zones were calculated for these wells using

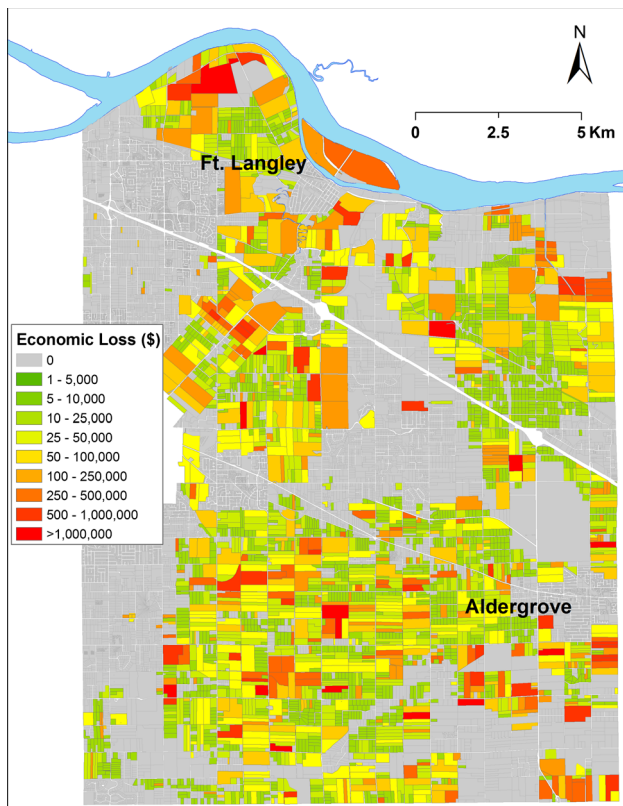


Fig. 9 Economic loss in dollars

Table 6 Rating table for assigning the total loss value (\$) to a loss class

Loss class	Loss value (\$)
0	No loss
1	<5, 000
2	5–100,000
3	10,000–25,000
4	25,000–50,000
5	50,000–100,000
6	100,000–250,000
7	250,000–500,000
8	500,000–1,000,000
9	1,000,000–5,000,000
10	>5,000,000

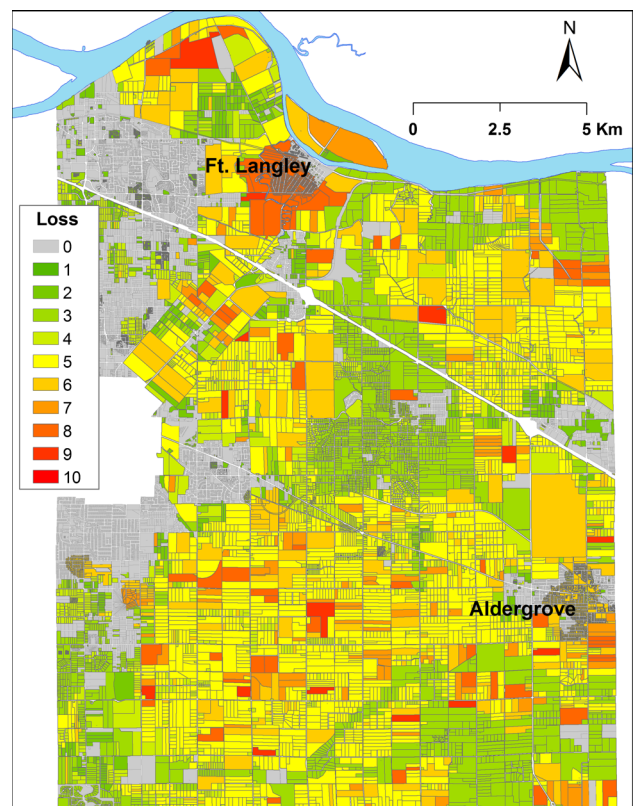


Fig. 10 Total loss for the base case scenario, reclassified using a 1–10 scale

a simple fixed radius method (BC Ministry of Environment, Lands and Parks 2000). This method calculates a circular capture zone based on the pumping rate, time of travel and basic aquifer properties (porosity, thickness). The result does not consider the flow of groundwater and is thus the best used in areas of low hydraulic gradients. Pumping rates were estimated based on the inferred number of people served and were often overestimated to remain conservative. This travel time only includes travel below the water table, not from surface through the vadose zone, and thus represents travel time significantly longer than 1 year (i.e. more conservative). The use of fixed radius capture zones may adequately represent the connection between hazards and specific wells in unconfined aquifers, but will be insufficient for wells drawing from confined units.

The loss assigned due to healthcare cost is based on the number of people using a well (inferred from land use or using Fraser Health Authority classification) multiplied by the average cost per case of GI-related illness of \$1,342.57 (Henson et al. 2008). If a pathogen-related hazard is located within the well capture zone, the property is assigned a loss.

With the widespread presence of pathogen hazards, these loss results (Fig. 11) are heavily weighted to the areas

with large groundwater extractions, most predominantly the municipal wells. They also highlight the potential losses to moderate extractors such as the schools that maintain a well water supply as well as the large number of small private wells.

Overall risk

Results

Using Eq. 1, vulnerability and loss were combined to calculate risk for the base case and health scenarios (Fig. 12).

For the base case, much of the Township is assessed a moderate hazard score (Fig. 6a), due to the predominance of agriculture over the total Township area. Because of this, the areas of high risk (Fig. 12a) are those that received high scores in aquifer susceptibility and loss. The few parcels of high hazard threat (e.g. service stations, small landfills) did transfer into a high risk score; however, the small size of these parcels is not evident in Fig. 12a. A notable area of high risk is south of Aldergrove, where high value agriculture is occurring far from municipal services over portions of the unconfined and susceptible Abbotsford-Sumas aquifer. Another high-risk area is in and around Fort Langley, where a highly susceptible aquifer is tapped by a high density of wells; the highest producing Township production well is located in this aquifer. Areas of moderate to high risk (risk score of 7–9) are generally those that received a value of 8 or higher in both the loss and vulnerability assessments; values of 10 were reserved for those few that also received a value of 8 or higher in hazard threat.

The result of health risk (Fig. 12b) emphasizes the areas near municipal extraction wells and other major pumping wells, due to the large number of people potentially exposed to pathogens. What these results do not include are the water system-specific safeguards that would drastically reduce the probability of a pathogen reaching an end-user. A majority of the larger municipal and community systems use some combination of chlorine, UV, reverse osmosis and/or ozone to prevent user exposure.

This use of multiple scenarios highlights the flexibility of the risk assessment method. Regardless of how the assessment of susceptibility, hazards and loss are completed, each input is ranked (scale of 1–10) and then combined within a GIS. The resulting risk maps provide a means of guiding risk management efforts within the study area. Because the ranking of the inputs is based on a relative scale, the resulting risk analysis is not necessarily comparable with other study areas; the tradeoff of this characteristic is that the method can be applied in areas with low data availability, using simpler techniques for assessing susceptibility, hazards and loss.

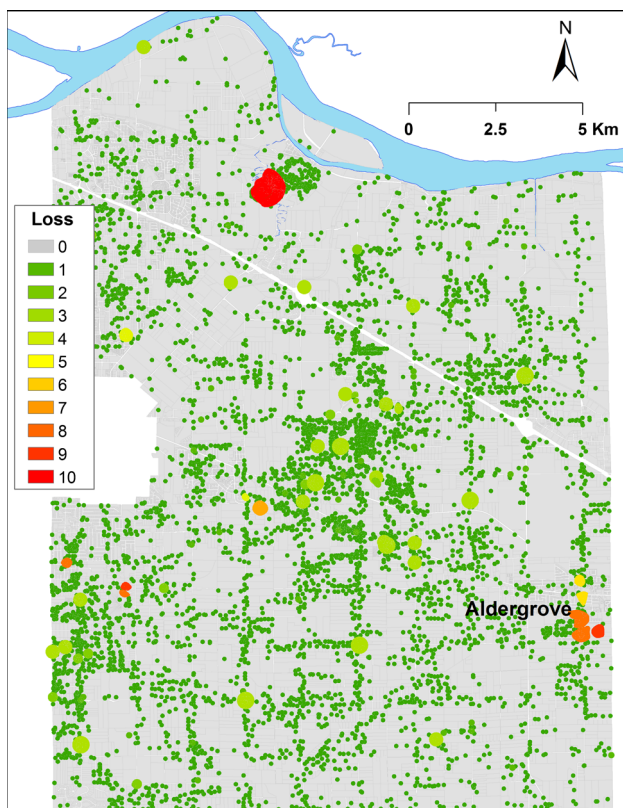


Fig. 11 Loss due to healthcare costs, reclassified using a 1–10 scale

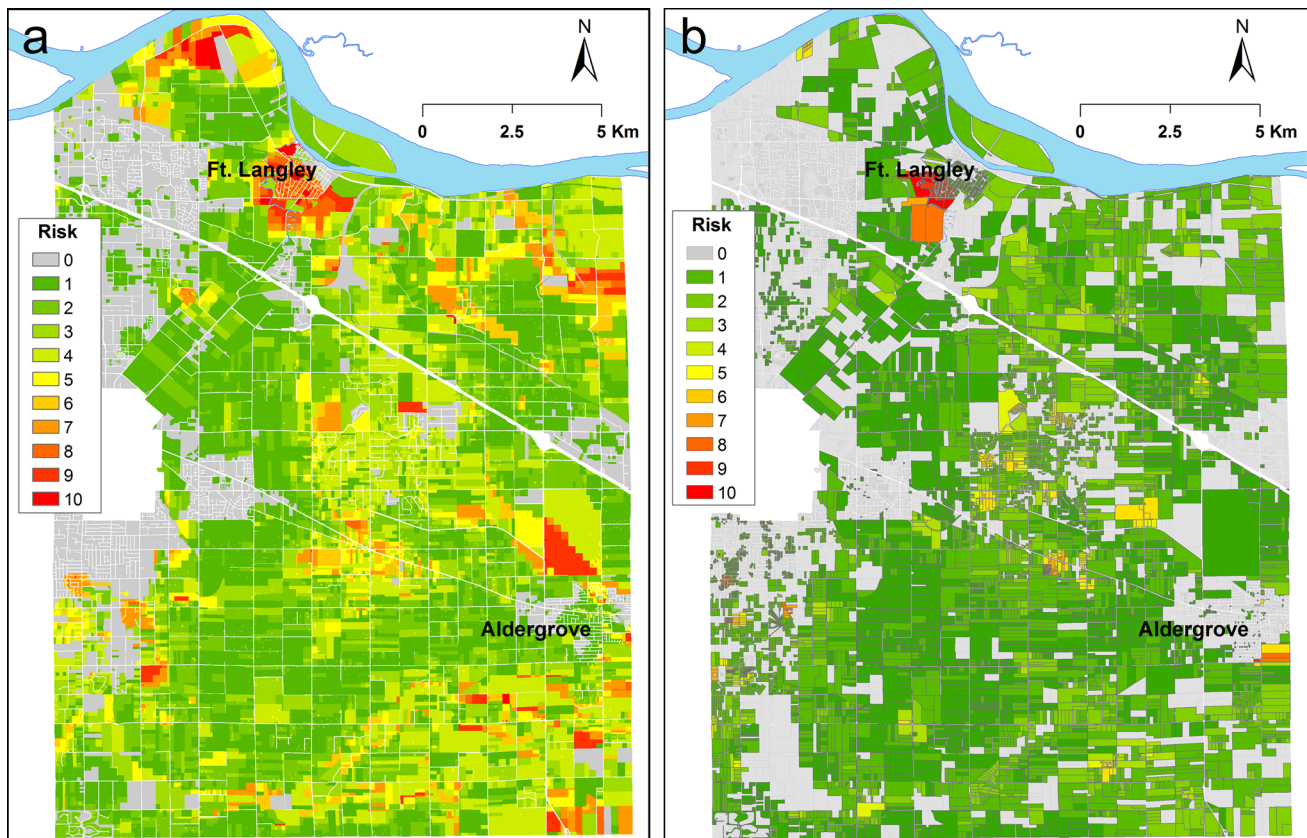


Fig. 12 Final risk map for the base case (a) and health (b) scenarios

Resistance and capacity

Both fundamental components of risk, vulnerability and loss, are in part dependent on the social, economic and governance structure of the local community. Therefore, this assessment can be used to direct management changes, to reduce a community's exposure to risk.

The effectiveness of human measures to protect the aquifer from contamination defines the resistance of a community. For example, the susceptibility of an aquifer can be altered by changing the potential impact of conduits. The high well density in and around Ft. Langley is believed to be associated with abandoned wells which have a high potential to act as conduits. Management options to address this increased susceptibility include focused education towards well owners in the area or increased enforcement of well closure requirements. To increase resistance to the identified hazards, each contaminant can be matched with a management strategy, to reduce contaminant quantities, extents or probability of release in certain areas. Regulatory examples include mandating secondary containment of storage facilities, nutrient management plans or spill response plans. Increased education towards the public and industry may

also reduce the likelihood of contamination. For example, areas of high septic density could become a focus for educating homeowners about septic maintenance. Looking to the future, land use planning could consider aquifer susceptibility when making land use designation changes.

The effectiveness of the community's response and recovery capability defines the capacity. This variable is largely hazard-independent and affects risk through loss. For example, those communities with alternative sources of water are susceptible to less loss and, therefore, have lower risk exposure. To increase capacity, the Township might upgrade the municipal water lines to handle agricultural needs, extend municipal lines into rural areas for potable use, or procure surface water licenses as agricultural water reserves. The water utility may reduce its exposure to loss by building greater water redundancy through increased extraction capacity, by undertaking wellhead protection planning or otherwise building backup systems.

Resistance and capacity then, indirectly affect how the variables for vulnerability and loss, respectively, are assessed; Eq. 7 expresses this relationship in a general fashion.

$$\text{Risk} = (\text{vulnerability} - \text{resistance}) \times (\text{loss} - \text{capacity}) \quad (7)$$

Through changes to resistance and capacity, a community's vulnerability and loss and, subsequently, overall exposure to risk can be strategically reduced over time.

Conclusions

The susceptibility of an aquifer to contamination is a function of the physical system. Man-made features can also provide preferential pathways (referred to as conduits) into the subsurface; wells, acting as pathways, were shown to increase the susceptibility of an aquifer on the small scale. When susceptible aquifers are located near contaminant sources, they become vulnerable to contamination. Using widely available land use data, potential contaminant hazards were identified across a large study area, and assessed based on their likelihood of release and ability to cause harm. If an aquifer is contaminated, there are a series of consequences that are not spatially uniform. Based on several aspects of monetary loss due to resource contamination, the consequence of contamination was mapped, revealing several important areas. By combining vulnerability with loss, a level of risk was mapped across the study area. Due to the equal weighting of both vulnerability and loss, only areas considered moderate to high in both aspects were assigned high risk values. In other words, only areas with a high potential consequence of contamination are considered at high risk, often despite a high susceptibility of the physical system. Similar to other risk assessments, a limitation of this methodology is that the final risk maps cannot be validated, as they represent a potential, both in terms of likelihood and severity, of resource loss. These results were used to identify potential problem areas, and to make suggestions of how to focus efforts to build capacity and resistance to groundwater contamination. The assessment then is an indicator of the current status of risk, but also a tool to inform change.

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