DRASTIC-Fm: a modified vulnerability mapping method for structurally controlled aquifers in the southern Gulf Islands, British Columbia, Canada

S. C. Denny · D. M. Allen · J. M. Journeay

Abstract DRASTIC, the methodology for mapping the intrinsic vulnerability of aquifers, is modified to incorporate the structural characteristics of fractured bedrock aquifers. In these aquifers, groundwater flow is predominantly through fractures, with large-scale fracture zones and faults acting as primary conduits for flow at the regional scale. The methodology is applied to the southern Gulf Islands region of southwestern British Columbia, Canada. Bedrock geology maps, soil maps, structural measurements, mapped lineaments, water-well information and topographic data, assembled within a comprehensive GIS database, form the basis for assigning traditional DRASTIC indices, while adding the structural indices necessary for capturing the importance of regional structural elements in recharge and well capture zone determinations.

Résumé La méthode DRASTIC, destinée à la cartographie de la vulnérabilité intrinsèque des aquifères, a été modifiée afin d'intégrer les caractéristiques structurales d'aquifères de socle fracturés. Dans ces aquifères, les eaux souterraines cheminent essentiellement par les fractures, et les secteurs fracturés et les failles jouent le rôle de drains à l'échelle régionale. Cette méthode a été appliquée à la région sud des Iles Gulf (sud-ouest de la Colombie Britannique, Canada). Les cartes géologiques du socle, les cartes pédologiques, les levés structuraux, les linéaments cartographiés, les informations sur les points d'eau et les données topographiques ont été réunies dans une base de données exhaustive. Ils forment ainsi la base d'attribution des indices DRASTIC traditionnels, et introduisent les indices structuraux nécessaires pour appréhender l'importance des éléments structuraux régionaux dans la détermination des zones d'alimentation et d'appel des puits.

Resumen Se ha modificado DRASTIC, la metodología para cartografiar la vulnerabilidad intrínseca de acuíferos, incorporando las características estructurales de acuíferos fracturados. En estos acuíferos, el flujo de agua subterránea se produce fundamentalmente por las fracturas, con zonas de fractura a gran escala y fallas que actúan como conductos primarios del flujo a escala regional. La metodología se aplica en el sureste de las Islas Gulf, región del Suroeste de British Columbia, Canadá. Los índices tradicionales en DRASTIC se asignan mediante mapas geológicos, mapas de suelos, medidas estructurales, cartografía de los lineamientos tectónicos, información sobre los puntos de agua y datos topográficos, unidos dentro de una base de datos vinculada a un SIG, mientras que añadiendo índices estructurales se refleja el peso de elementos estructurales regionales en la recarga y en las determinaciones de las zonas de captura de los pozos.

Keywords DRASTIC · Aquifer vulnerability · Fractured rocks · Faults · Gulf Islands · British Columbia · Canada

Introduction

The dynamic and hidden nature of groundwater often impedes the understanding and management of this vital resource. An initial step toward sustainable groundwater-resource management involves understanding the hydrogeologic nature and mechanics of the resource. Regional-scale assessments, such as vulnerability maps, have proven to provide an effective means of assembling key information assets, identifying environmental trends, and prioritizing the need for detailed site-specific investigations within groundwater environments (Bekesi and McConchie 2002; Aller et al. 1987). However, while the methodologies for undertaking vulnerability assessments are reasonably well-developed for unfractured aquifers, standard approaches for rep-

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resenting fractured bedrock aquifers are currently limited.

Within this paper, we present a modification to an existing aquifer vulnerability mapping methodology, namely DRASTIC, which identifies the impacts of structurally controlled aquifers on the quality of groundwater resources. We demonstrate the application of this modified methodology through a case study in the southern Gulf Islands in southwestern British Columbia, Canada. It is anticipated that the straightforward nature of this framework will support the uptake and use of model outputs at decision-making levels as well as support the application of this modified methodology in other study areas with similar physical characteristics.

Background

Study area

Like many communities situated in close proximity to urban centres, the southern Gulf Islands, located in the Georgia Strait between Vancouver and Victoria (Fig. 1), are experiencing significant development pressures. Groundwater quality issues in the Gulf Islands have been amplified by improper disposal of agricultural waste, failed septic systems, pesticides, and saltwater intrusion due to both natural conditions and over-pumping. The subdued topography of the Gulf Islands lends itself to the presence of few lakes that can support domestic and agricultural uses; thus, the majority of residents rely on fractured bedrock aquifers as a primary source of freshwater.

The geology and hydrogeology of this region have been researched extensively (e.g., Allen et al. 2003a; Mackie 2002; Mackie et al. 2001; Journeay and Morrison 1999; England 1990; Dakin et al. 1983; Hodge 1995); however, the complex nature of this information could not be easily translated by decision-makers to support land-use planning objectives in defining regions on the islands where new developments could be located with minimal adverse impacts on the surrounding groundwater environment. A regional-scale evaluation of the potential for groundwater contamination became an important step in synthesizing all available information while supporting this process.

Aquifer vulnerability mapping

Vulnerability mapping, while receiving some criticism internationally and largely on account of uncertainty surrounding the definition of the term "vulnerability", is nonetheless a common method for representing spatially and semi-quantitatively the relative susceptibility of an aquifer to contamination from surface sources. Assessment of vulnerability is based on the environmental characteristics of a landscape that facilitate or impede contamination, and represents the "likelihood of a contaminant to reach a specified position in the groundwater system after introduction at the surface" (National Research Council 1993 in Bekesi and McConchie 2002).

Although there is a higher degree of scientific soundness in "specific" vulnerability maps for specific pollutants (e.g., Foster 1987; Canter et al. 1987), it has been recognized that generally there is insufficient available data to perform specific vulnerability mapping. Consequently, generic mapping systems have been developed that are simple enough to apply the available data, and yet are capable of making best use of those data in a

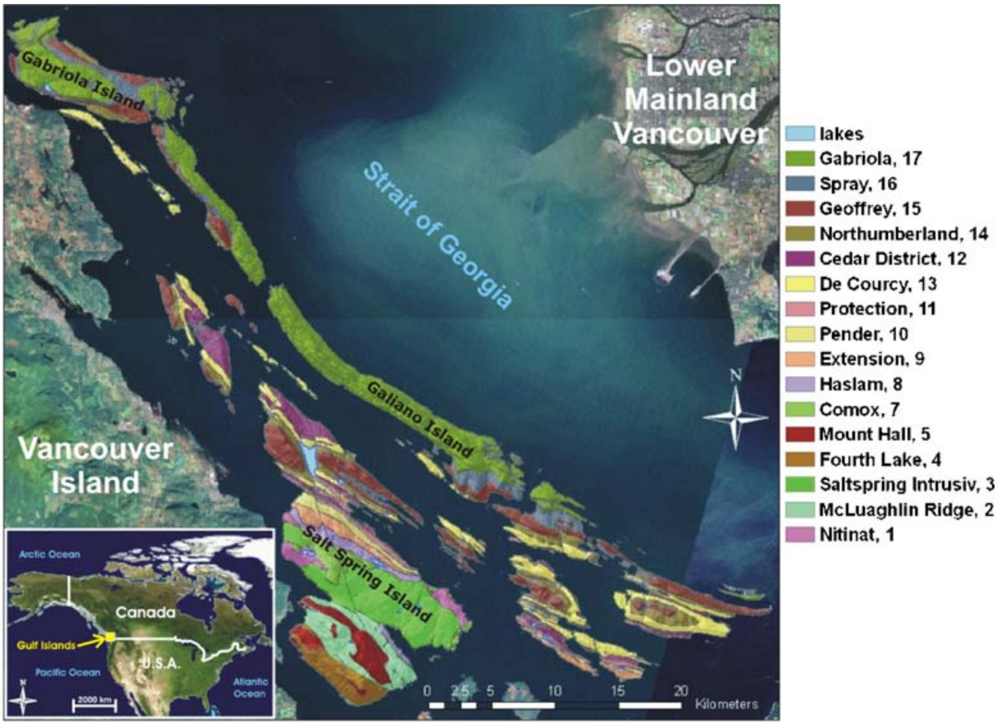

Fig. 1 Geology map of southern Gulf Islands (Journeay et al. 2005). The colour coding on the right indicates the geological formations of the Gulf Islands. The numbering refers to the sequence of deposition for each of the formations and corresponds to the stratigraphic column shown in Fig. 2

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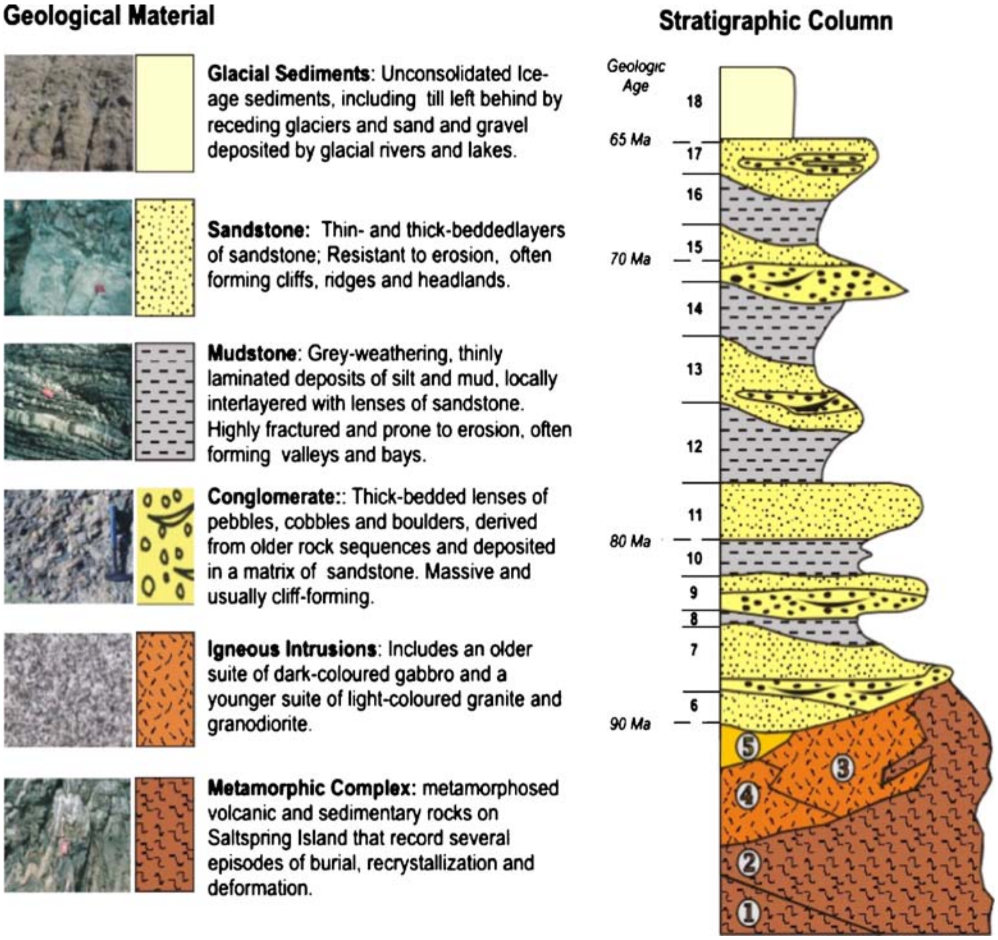

Fig. 2 Nanaimo Group stratigraphy and geological map Legend (modified from Mustard 1994). The corresponding names of the geological formations are found in Fig. 1

technically valid and useful way. Various systems of vulnerability evaluation and ranking have been developed and applied in the past including AVI (van Stempvoort et al. 1992), DRASTIC (Aller et al. 1987), EPIK (Doerfliger et al. 1999) and ISIS (Civita and De Regibus 1995). Such vulnerability methodologies take into account that the natural environment protects itself when a contaminant is introduced. The groundwater system can be classified into three stages based on the origin-pathway-target model: (1) contaminants enter the system and constitute the threat, (2) soil and rock above the water table form a barrier to contaminants percolating down from the surface, and (3) the groundwater resource below the water table that may be damaged if contaminants penetrate the barrier (Piscopo 2001). The purpose of groundwater vulnerability assessments is to characterize the contamination potential within a geologic setting and define areas that are more vulnerable than others. This type of assessment does not consider the properties or characteristics of contaminants (Bekesi and McConchie 2002; Piscopo 2001).

Table 1 DRASTIC-Fm parameter definitions and weights

Hydrogeologic factor	Weight
D depth to water	5
R net recharge	4
A aquifer media	3
S soil media	2
T topography	1
I impact of vadose zone media	5
C aquifer hydraulic conductivity	3
Fm fractured media	3

Developed by the US Environmental Protection Agency (EPA), DRASTIC is an aquifer vulnerability methodology that parameterizes the physical characteristics that impact groundwater pollution potential (Aller et al. 1987). The term “DRASTIC” is an acronym for seven model parameters (Table 1).

During the preliminary phases of the model-development process, several alternative aquifer vulnerability frameworks were considered including the aquifer vulnerability index (AVI) methodology (van Stempvoort et al. 1992). The AVI method relies quite heavily on well data to develop the spatial representation of aquifer vulnerability in a study area. Due to the sparse nature of the well data available for the Gulf Islands coupled with the difficulty in applying interpolation measures across discrete island boundaries, the reliance on well data proved to be a barrier to applying the AVI methodology. Furthermore, a comparison study of the DRASTIC and AVI methodologies concluded that the two methodologies yielded similar results in a study area in British Columbia (Wei 1998).

More recent methodologies have been developed to represent aquifer vulnerability in karst landscapes (EPIK and ISIS). Although karst landscapes bear some similarities to fractured bedrock environments, aquifer vulnerability methodologies for karst landscapes are distinct in their application and would not apply to the Gulf Islands. A comparative study completed in 2003 (Gogu et al. 2003) evaluated the applicability of several aquifer vulnerability methodologies in a karst study area including EPIK and DRASTIC. The conclusions from this work state: "Progress is needed to better differentiate fissure matrix from compact rock and from major discontinuities or karst conduits" (Gogu et al. 2003, p 891). Finally, in combination with the above mentioned factors and its successful application in study areas across Canada (Murat et al. 2004; Wei et al. 2004), DRASTIC was determined to be the most suitable methodology for assessing aquifer vulnerability in the Gulf Islands.

Regional geologic setting

Physiography and geology

The Gulf Islands are a group of 40+ islands that range in area from ~1-75 km^2 and are characterized by a generally NW–SE trend and elongation defined by linear ridges and valleys. Elevations range from 100 to 200 m, reaching a maximum of about 350 m on Saltspring Island. Coastlines are typically rocky, with either long expanses of low relief bedrock sloping shallowly into the ocean or, alternatively, steep cliffs and narrow rocky beaches.

Rocks of two general types underlie the southern Gulf Islands: Paleozoic to Jurassic arc-related igneous and sedimentary rocks, and Upper Cretaceous marine sedimentary rocks (Fig. 1). Arc-related rocks of the Wrangellia Terrane are present locally on Saltspring Island as fault-bounded wedges structurally juxtaposed with sedimentary rocks of the Upper Cretaceous Nanaimo Group, and as "basement" unconformably overlain by the Nanaimo Group. The sedimentary sequence is up to 4 km thick and comprises conformable and laterally intertonguing successions of sandstone and conglomerate formations, separated by mudstone and siltstone formations (Fig. 2). As such, the Nanaimo Group formations do not represent a true "layer cake" stratigraphy, but are composed of laterally thickening and thinning units with both conformable and sharp, erosive contacts. Lithology in the Nanaimo Group varies in grain size both between and within formations. Sandstone-dominated formations (e.g., Gabriola Formation, dominantly massive sandstone) contain little structure, and can attain thicknesses of hundreds of metres, with only minor fine-grained interbeds. Silts and muds dominate mudstone formations (e.g., Spray Formation) with significantly lower bed thickness (mm–cm).

Unconsolidated deposits, of dominantly glacial and/or marine origin do not constitute a volumetrically significant percentage of the exposed geology on any of the islands, yet are anticipated to have a significant control on recharge. The thickest deposits occur in lowlands between ridges where they may reach 30 m (Hodge 1995). Over a majority of the islands, surficial cover has been eroded down to, or nearly down to, bedrock.

Structure

The present distribution of Nanaimo Group formations is the result of multiple regional deformational events (e.g., Journeay and Morrison 1999). Additionally, the Gulf Islands have undergone glacial isostatic deformation in response to multiple Quaternary glaciations (Clague 1983), which have resulted in upwards of 50 m of vertical isostatic rebound.

Structurally, the Gulf Islands are characterized by gentle folds with bedding that dips in the range of 5–15°, with numerous small- and large-scale discrete fractures and faults. Mackie (2002) summarized the results of a detailed fracture mapping study on the southern Gulf Islands in which fracture data were collected using a linear scan-line technique from 157 stations, incorporating all formations of the Nanaimo Group (with the exception of the basal Comox Formation), and spanning all of the eight southern Gulf Islands. Over 8,000 measurements of fractures were made. Generally, stations were chosen to minimize bias that may have resulted from orientation of coastline exposures, and when possible, different stations were located on mutually perpendicular coastline exposures.

Both chain map and outcrop analyses indicate that the distribution of fractures, defined by spacing between fractures, is not spatially or lithologically homogenous. Fracture density, measured as number of fractures per metre chain length, varies both in relation to structural setting, especially in relation to large faults and in joint zones, and with changes in lithology.

Bedding perpendicular joints

Bedding perpendicular joints, found at all stations, vary in density both within a specific lithology/formation and between lithologies (Mackie 2002). Higher joint densities were observed in the more thinly bedded mudstone-dominated units, notably within the transition zones between formations where mudstone bedding thickness is generally small. This suggests that thinly bedded mudstone-dominant units may have a higher permeability where they are in contact with sandstones. In contrast, the sandstone-dominated formations, with much lower fracture densities, may act more as impermeable blocks with significantly more widely spaced discrete flow zones or pathways. In this respect, intra-formation heterogeneity, in the form of fine-grain interbeds within coarse-grain formations, may create pockets of more highly fractured rock, which, if connected to a recharge zone, may form an "intra-formation" aquifer. Similarly, at the contacts between formations, where there is transitional bedding, there may be enhanced permeability.

Discrete fractures, fracture zones and faults

Many mesoscale fractures were identified on the islands that may represent discrete flow paths or narrow (metre-scale) flow zones. These small structures have variable offset up to approximately 5 m, and only minor changes in fracture density associated with them. The structures are not visible on 1:75,000 scale airphotos or on a DEM (digital elevation model). Flow along these structures is interpreted to be more like a discrete path or conduit, and may be of a relatively short length, perhaps up to a maximum of tens of metres. Additionally, these structures cross-cut all formations and are considered to represent a separate level in a hierarchy of structure-controlled flow. However, it is hypothesized that discrete fractures, which tend to be older than lineament-scale fault and fracture zones described below, may not have as significant an effect on groundwater flow at the island scale, but may be important at the local scale.

Structures visible at the 1:75,000 (regional scale) can be characterized on the ground as fault or fracture zones up to tens of metres in width. These structures are often identified by lineaments that are zones of high weathering or ridges. Variation of fracture density with proximity to faults is common (Caine et al. 1996), and on the Gulf Islands it was found that fracture density tends to increase by at least a factor of ten in the presence of a regional-scale fault (Mackie 2002). Lithology appears to affect density as zones of high fracture density are dominantly in sandstone, while fracture density does not increase so dramatically in faults that cut mudstone-dominated units.

From a hydrogeologic perspective, fault and fracture zones can likely be represented at the regional scale as zones of high permeability arising from the high density and width of fracturing. These larger fracture zone structures are interpreted to have a significant effect on groundwater flow, particularly at the regional scale.

Hydrogeology and conceptual framework

The Nanaimo Group forms the majority of bedrock of the Gulf Islands, and consequently, the majority of the water-bearing units on the islands. Past investigations into the distribution of water resources (e.g., Allen et al. 2002; Hodge 1995; Dakin et al. 1983) and water-well drilling reports concluded that water is derived primarily from fractures as secondary permeability, reflecting the low primary porosity and permeability of the bedrock. All lithologies are highly cemented, dominantly by calcite, with primary porosity in outcrop averaging about 5%

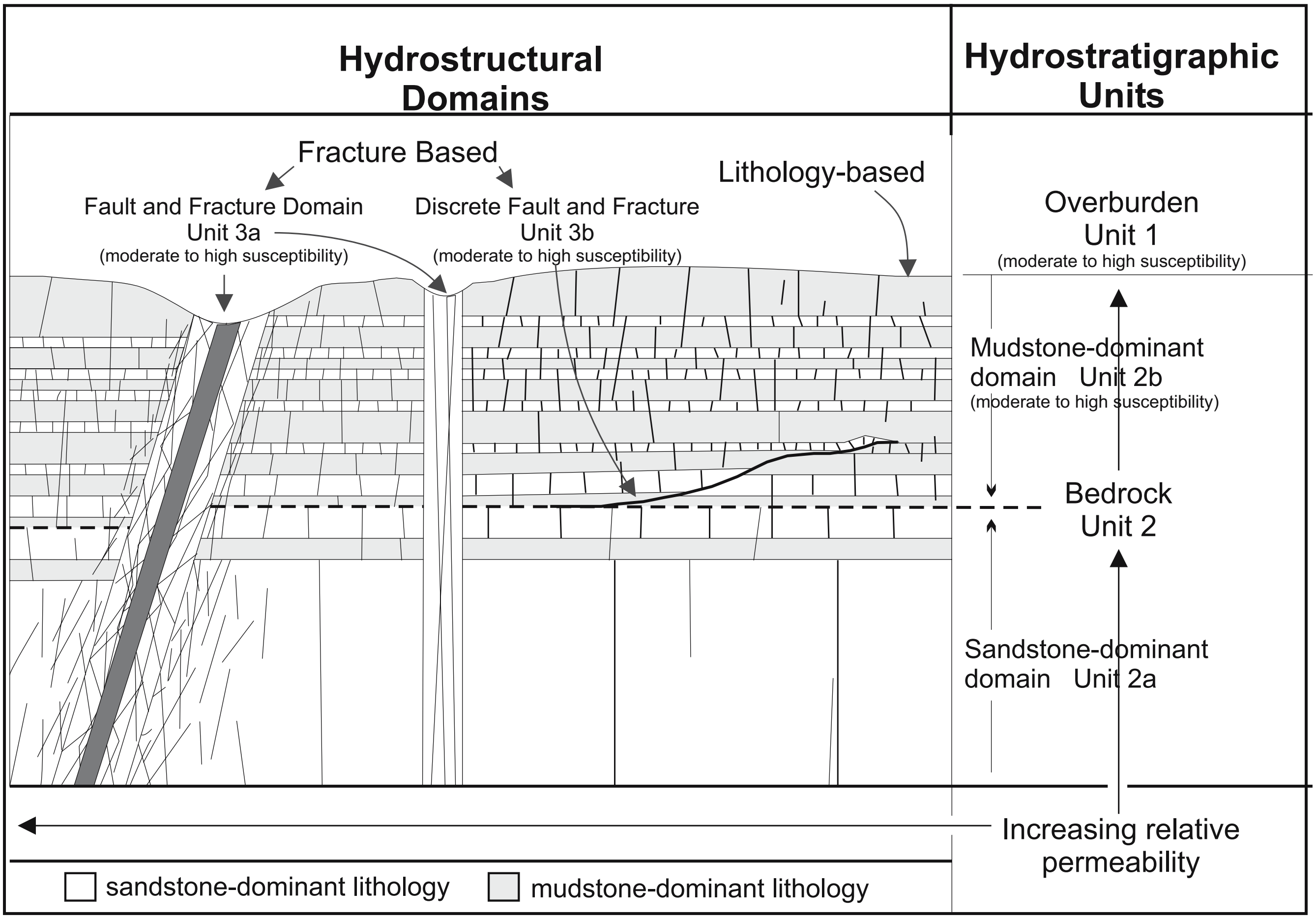

Fig. 3 Conceptual model for hydrostuctural domains of the Gulf Islands (Mackie 2002), modified from Journeay et al. 2004

(England 1990). Thus, vulnerability maps would best be represented with a conceptual model that captures permeability variations derived from fracturing at a range of scales.

To this end, Mackie et al. (2001) proposed a conceptual model for representing the hierarchy of fracturing exhibited in regional-scale bedrock aquifers. The model, which was later refined by Mackie (2002), is based on the concept of hydrostructural domains, as opposed to the more traditional hydrostratigraphic units concept commonly used in hydrogeological studies. The term "hydrostructural domain" is essentially equivalent to the term "structural domain", which is used within the structural geology community to represent bodies of rock with distinct structural characteristics. The prefix "hydro" implies a connection with permeability. Hydrostructural domains are defined on the basis of variation in fracture characteristics such as the orientation, aperture, or density of fractures, all of which contribute to permeability variations at a variety of scales. For example, in a regional aquifer, different domains may represent regions of differing fracture orientation, which might be associated with anisotropic permeability. Similarly, a discrete domain, superimposed over other domains, may be associated with a fault that has permeability several orders of magnitude greater than the surrounding aquifer material.

On the Gulf Islands, the concept of hydrostructural domains encompasses the lithologic and stratigraphic subdivisions, which observe variations in joint density, which are anticipated to relate to differences in permeability. Thus, three lithology-based domains, corresponding to (1) sandstone-dominant lithologies, (2) mudstone-dominant lithologies, and (3) interbedded sandstone and mudstone lithologies are needed to capture the observed variation in joint density. Where bedrock geology is uniform in a region, perhaps only one lithology-based hydrostructural domain would be required. In either case, the occurrence of lithology-based domains within a study region could be based on mapped geology, and appropriate permeability assigned based on continuum principles (i.e., the equivalent porous media approach) or a stochastic fracture distribution.

A second level of domain, namely a fracture-based domain, would correspond to discrete fractures, fracture

Table 2 Summary of DRASTIC parameter development

DRASTIC parameters	Parameter derivation description
D depth to water table	Due to spatial inconsistencies in the water-well database, interpolation methods could not be applied to depth to water values recorded in the water-well database. Taking into account the general principle that depth top-water values will be lower at the periphery of the islands and greater at the middle of the islands, a function was derived by comparing elevations extracted from the DEM and available water depths extracted from the water-well database. Depths for the "D" parameter range from 0 to 106 m (0–350 ft)
R net recharge	Rates of net groundwater recharge were calculated using the US Environmental Protection Agency's HELP (Hydrologic Evaluation of Landfill Performance model; Schroeder et al. 1994). This simple water-balance model simulates infiltration at the base of the vadose zone for specified surface conditions and soil-column geometries. Inputs into this model include climate data collected at the Victoria airport meteorological station (800 mm/year) and the properties of surficial and bedrock geology sequences derived from the water well database. Results from the HELP model are non-spatial; therefore, model outputs were applied to soil polygons to create a spatially referenced recharge map. Recharge rates in the region range from 102–533 mm/year (4–21 inches/year)
A aquifer media	The bedrock geology dataset for the Gulf Islands relied on helavilty to derive the aquifer media parameter. Based on the lithologies of the formations in the islands, each formation was assigned a DRASTIC rating. To capture the unique character of the higher permeability interbedded zones on the Gulf Islands, buffer zones were defined around all mapped formation contacts. The buffer zone width was based on field observations and extent of fracturing associated with interbedded zones
S soil	To derive the soil (S) parameter for the Gulf Islands, the soil datasets developed by Agriculture Canada (van Vliet et al. 1987, 1991; Kenney et al. 1988, 1990; Green et al. 1989) were used exclusively. Soil descriptions were used to assign DRASTIC ratings to all soil types in the region
T topography	Within DRASTIC, the topography parameter is measured in percent slope. Attributes within the soil dataset provided slope descriptions for each polygon within the dataset. It was determined that the percent slope descriptions within the soil dataset would be applied to represent the T parameter due to the detailed scale of the soil dataset and coherence with the S parameter
I impact of vadose zone	The DRASTIC methodology measures the impact of vadose zone parameter (I) by the velocity (metres/second) that water moves through the zone. The ranking of this parameter was determined by extracting the lithologies of the material encountered above the water table from the water well database. Queries were conducted to extract seven categories of material layering from the well log database; the queries were limited to well records which had static water levels recorded. Due to the sparse availability of water-well records with static water levels recorded, the water-well logs provided adequate information to understand the lithological sequences encountered above the water table. However, the locations of these wells were too sparse to create an interpolated map of hydraulic conductivities. To accommodate for these spatial issues and the unavailability of a surficial geology map for the region, polygon descriptions derived from the soil dataset were compared to sequences extracted from the water-well database. Associated hydraulic conductivities were applied to the spatial extents of the soil polygons. In the Gulf Islands, impact of vadose zone conductivity values range from 10^{-5} to 10^{3} m/s
C conductivity	Based on pumping tests performed on wells in the Gulf Islands, hydraulic conductivity ranges and geometric means were determined based on the aquifer material encountered in the well. These values were used as a reference to assign DRASTIC ratings to the bedrock geology dataset. Due to the relatively low permeability of rock in the Gulf Islands, few conductivity ratings were greater than 1

zones and faults, with corresponding ranges of permeability depending on the degree of fracturing associated with each mapped feature. These domains are overlain atop the lithology-based domains and represent the hierarchy in fracturing commonly observed as a result of multiple episodes of deformation or deformation mechanics. Such features could be identified using aerial photographs (lineament analysis), field mapping or three-dimensional geologic modelling. Once identified, appropriate hydraulic properties could be assigned to each of the fracture-based hydrostructural domain based on either pumping tests in wells that intersect such features or by discrete fracture analysis.

Figure 3 illustrates the conceptual model developed by Mackie (2002) and classifies the hydrostructural system in the Gulf Islands into five major components: Unit 1, thin unconfined aquifers located primarily in valley bottoms; Unit 2a, sandstone-dominant unit with low fracture density and reduced permeability; Unit 2b, mudstone-dominant units represented by high fracture density and elevated permeability; Unit 3a, cross-cutting fault zones and Unit 3b, discrete fault and fracture systems represented by relatively high permeability (Journeay et al. 2004).

The hydrostructural domain approach appears to be a reasonable one for the Gulf Islands based on over 100 pumping well tests analyzed on the Gulf Islands (Allen et al. 2003a). That study concluded that (1) the hydraulic properties were not significantly different for wells completed in mudstone- or sandstone-dominant formations; and (2) flow in most wells located near mapped lineaments were highly influenced by linear flow, and that the hydraulic properties calculated for wells situated near such features were consistently higher than those for wells away from lineaments. These observations support the interpretation that large-scale fault and fracture zones exercise a dominant control on the hydrogeology, and probably act as conduits for groundwater flow at the regional scale.

Methodology

Implementation of DRASTIC-Fm

As an index-based model, DRASTIC assigns relative weights to each of its parameters. These weights are allocated based on a parameter's contribution to the overall susceptibility of an environment. Within each parameter, ratings are assigned to define the significance of one characteristic over another.

Ratings for individual parameters were determined from direct consultation with the DRASTIC EPA manual (Aller et al. 1987) and from the application of DRASTIC to other study areas within similar environments in British Columbia (Wei et al. 2004; Allen et al. 2003b).

In order to properly represent the parameters within the DRASTIC methodology from a spatial context, a comprehensive collection of Geographic Information System (GIS) datasets were compiled. Key input datasets into this model include soil, bedrock geology, a water well database and a DEM. In order to bring consistency to

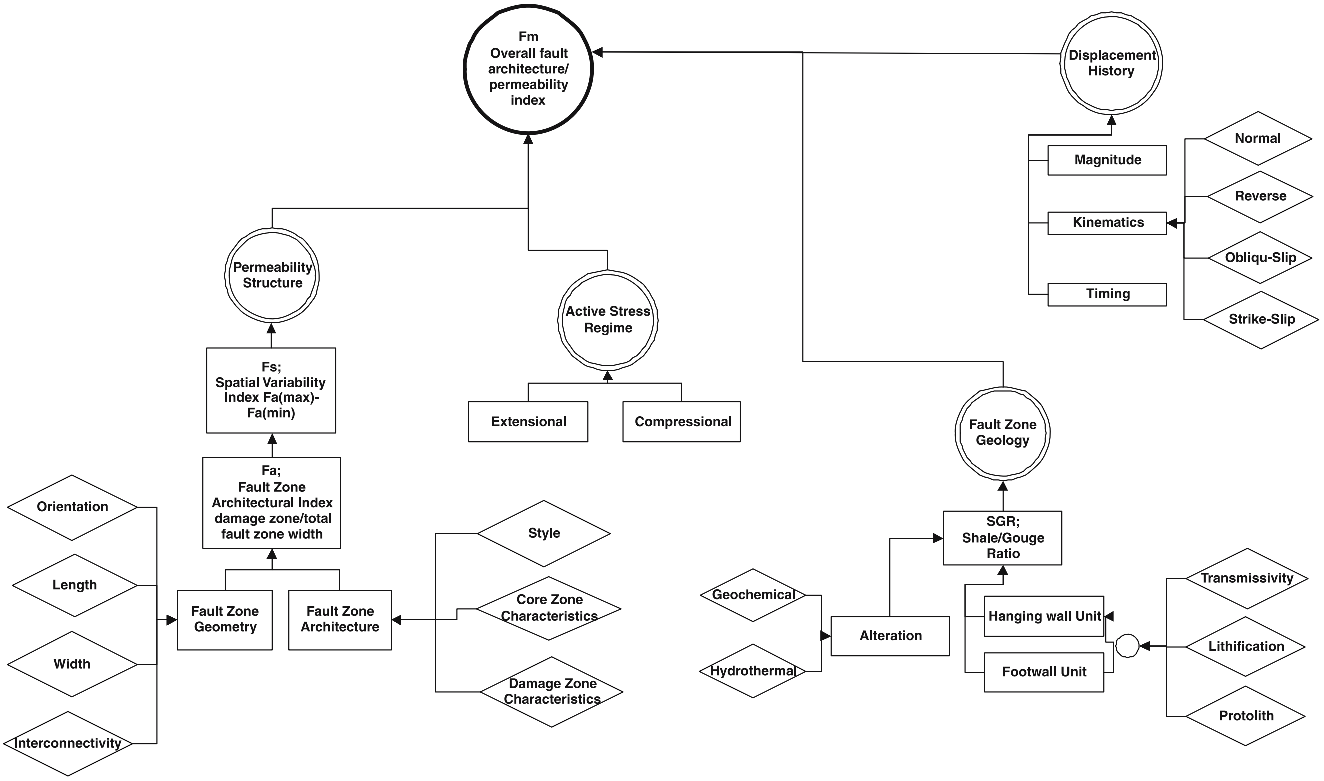

Fig. 4 Conceptual framework for the derivation of the fractured media (Fm) parameter

the varying scales of the input datasets, a constant scale was determined by the DEM (25 metres) and each of the layers were converted to raster datasets. Each cell in the model output dataset is represented by a vulnerability value, which corresponds to the cumulative rating of all parameters. Model outputs were then classed based on their levels of vulnerability.

Table 2 describes the procedures undertaken to develop the traditional seven parameters of the DRASTIC methodology (D, R, A, S, T, I, C). For the purpose of this paper, focus will be put on the development of the Fractured Media (FM) component and how this parameter was integrated into the existing DRASTIC methodology.

Fm-fractured media

The impact of discrete fractures, fracture zones and faults on the quality of a groundwater resource can be represented generally in the description of the "A" (aquifer media) parameter of the existing DRASTIC methodology. However, the spatial extent and characteristics of fault and fracture systems are not explicitly represented (Aller et al. 1987; Wei 1998). By applying the existing DRASTIC methodology to the Gulf Islands, a significant piece of the hydrogeological story would be missing. To rectify this, DRASTIC was modified to include an additional parameter-fractured media (Fm). Fm takes into account three primary characteristics that dictate the impact of a discrete fracture network: orientation, length and fracture density (Singhal and Gupta 1999). These three characteristics are combined into an eigth DRASTIC parameter and assigned the same weight as aquifer media (see Table 1). This modified methodology has been termed DRASTIC-Fm.

The design of the Fm parameter required the development of a conceptual framework to assess all of the characteristics that needed to be addressed in order to adequately represent the impact of fault and fracture systems in a modified DRASTIC methodology. The details of this framework are described in Fig. 4. Several aspects of the framework were derived from Caine et al. (1996) and formed the basis for representing the spatial variability and fault zone architecture indexes of the permeability structure. For the purpose of the Gulf Islands case study, not all aspects of the framework were able to be represented due to the availability of information sets for the region. Specifically, focus was made on the permeability structure and active stress regime components of the framework. This framework provides an opportunity for alternative case study areas with additional information to expand the scope of the Fm parameter for their test site.

The locations and extents of fault and fracture systems represent the key to properly representing the Fm parameter in any study area. Localized field studies conducted throughout the Gulf Islands (Mackie 2002; Journeay and Morrison 1999) significantly supported the derivation of the parameter; however, not all faults and fractures can be derived from "on the ground" investigations. A more regional representation was needed. The use of remote-sensing information has become a commonly used technique in supporting the collection of structural data. Methods of remote-sensing data collection permit the delineation of regional features and trends, provide representation for areas that may be inaccessible by field investigations, and save considerable time and resources when analyzing a large study area (Singhal and Gupta 1999).

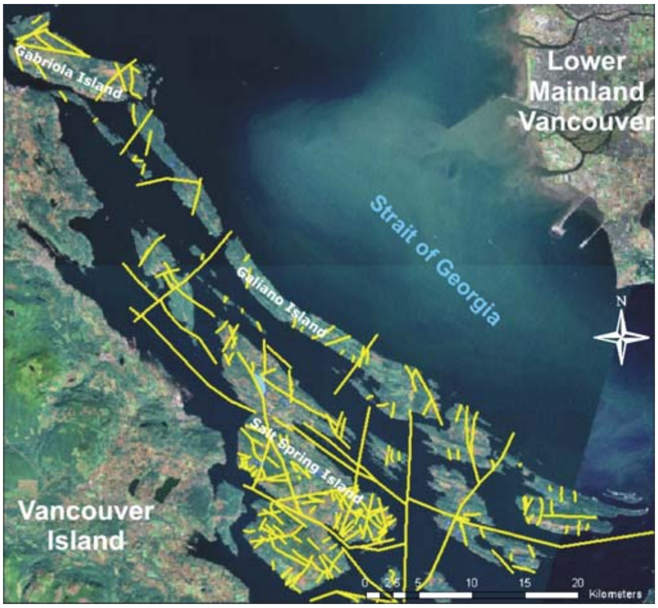

Fig. 5 Lineament and fault network for the southern Gulf Islands

The lineament analysis applied to the Gulf Islands incorporated a 25-m resolution DEM and 12.5 m Landsat 7 Thematic Mapper multispectral panchromatic imagery. A hillshade was computed from the DEM to extract features of the landscape through the use of shadowing and sun-angle illumination. By calibrating the hillshade to several different sun angles, different structural characteristics could be identified. Areas of dense vegetation cover can often act as a barrier to the identification of linear features using remotely sensed datasets. Some regions in the Gulf Islands experience quite dense land cover, to

Table 3 30° fault orientation classification and associated DRASTIC-Fm ratings

Orientation/azimuth			
Extension	Min	Max	Rating
	285	315	7
	315	345	10
	345	15	7
	105	135	7
	135	165	10
	165	195	7
Contraction	195	225	4
	225	255	2
	255	285	4
	15	45	4
	45	75	2
	75	105	4

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Table 4 Length classifications and associated DRASTIC-Fm ratings

Length (m)	Rating
20,000–25,000	10
15,000–20,000	8
10,000–15,000	6
5,000–10,000	4
0–5,000	2

overcome this, a multispectral image using the infrared band 4 was employed to identify distinct vegetation patterns caused by fault-altered drainage patterns and preferential moisture movement produced by the presence of a fault plane (Campbell 1996). As a means of ground-truthing, the final lineament analysis was compared and combined with structures mapped in the field. The final Gulf Islands structural dataset represents fault and fracture zones as well as discrete structures (Fig. 5).

Fracture orientation The orientation of faults and fractures plays a key role in determining whether a fault acts as a hydraulic conduit or barrier to groundwater contamination. Extensive field research was performed by the authors examining the characteristics of fault and fracture systems in this study area. Results of this research were published by Journeay and Morrison (1999) where faults and fractures present in the Gulf Islands were classified into zones of contraction and zones of extension based on their orientation. Within this hypothesis (Journeay and Morrison 1999), NE–SW trending faults were considered to have a high fault aperture and NW–SW trending faults were considered to have a low fault aperture. The results of this work were further collaborated by identifying elevated yields from wells located on major faults in the region. In order to represent this hypothesis spatially, an algorithm was applied to calculate the two-dimensional azimuth of all faults present in the structural dataset for the Gulf Islands. Orientations were divided into 30° increments; DRASTIC ratings reflect the proximity to zones of extension or contraction (Table 3).

Fracture length The length of a fracture determines whether it is a regional or discrete structure. Regional structures often contain several fault intersections, and this can significantly increase the hydraulic conductivity of a fault. Within a GIS, the lengths of all faults were calculated and assigned DRASTIC-Fm ratings (Table 4). Length classifications were determined on the clusters of lengths calculated for the structural dataset.

Fracture intensity Based on the conceptual model of Mackie (2002), it was determined that fracture intensities increased with proximity to known faults (Caine et al. 1996). Mackie (2002) calculated minimum and maximum fracture density values (fractures/m) for dominant formations in the Gulf islands from scan-line data. To represent the gradation of minimum to maximum fracture density with proximity to faults, buffer distances were assigned to all structures in the dataset. The geological formations within each of those buffers were derived from the Gulf Islands bedrock geology dataset (Journeay et al. 2005). Buffer distances were determined by referencing the resolution of the DEM used in the development of the lineament analysis. Fault and fracture zones visible on the DEM were considered to have greater zones of fracture density because they were visible at a larger scale and, therefore, were assigned buffer distances greater than the

Table 5 Fracture density classifications and associated DRASTIC-Fm ratings

Fracture density (fractures/m)	Rating
0–2	2
2–4	4
4–6	6
6–8	8
>8	10

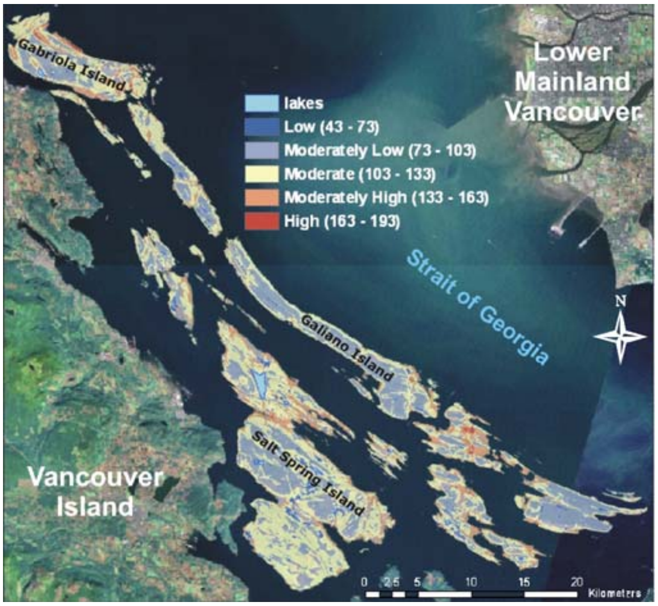

Fig. 6 Drastic-Fm model result

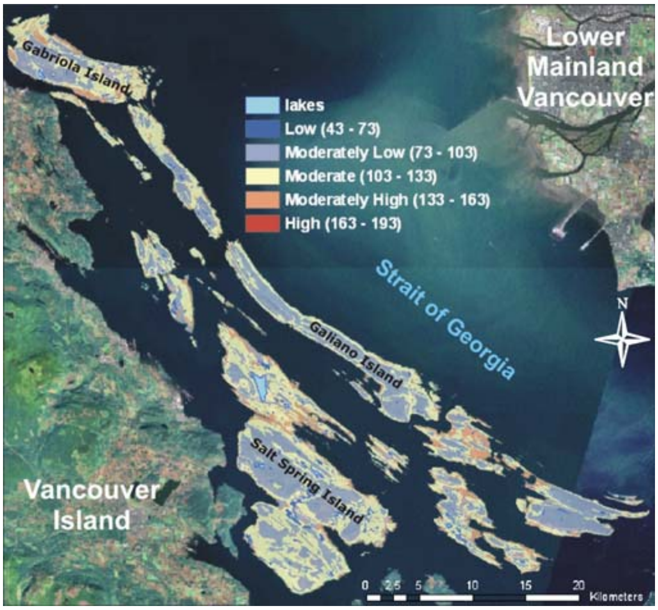

Fig. 7 DRASTIC model result, fractured media (FM) parameter not included

resolution of the DEM. All other structures represented those mapped in the field and were considered to be local or discrete. These local structures were given buffer distances representing the resolution of the DEM. Once fracture density values had been applied to all structures in the dataset, they were categorized into five classes and ratings were assigned (Table 5). The final Fm parameter was derived by combining the three characteristics discussed above. An average was calculated for the ratings to assign final Fm vulnerability values.

Results

By reviewing previous applications of the DRASTIC methodology in other study areas (Piscopo 2001; Osborn et al. 1998), DRASTIC-Fm model outputs were classified into five categories of vulnerability ranging from high to low. Due to the additional Fm parameter, minimum and maximum output ranges of the DRASTIC-Fm model (26–260) were inflated in comparison to the traditional minimum and maximum DRASTIC outputs (23–230). The final output dataset for the Gulf Islands (Fig. 6) identifies vulnerability rates ranging from 43 (low) to 193 (high).

General trends in the model outputs include regions of high vulnerability around island perimeters where instances of saltwater intrusion are prevalent, and in valley regions where the topography changes, recharge rates are high and structures are present. The model is quite sensitive to changes in the D (depth to aquifer) and the presence of faults and fractures (Fm).

Regions of moderate to low vulnerability (43–107; Fig. 6) exist primarily in poorly drained soil layers with significant clay deposits. These regions occur primarily in the central portions of the islands where the thickness of material above the aquifer is greater that 9 m (30 ft) deep. Bedrock formations that exhibit the lowest vulnerability rates include Pender, Extension, Protection, Buttle Lake and Sicker groups and the Mount Hall and Salt Spring Intrusive Suites (Figs. 1 and 2).

Regions of moderately high to high vulnerability (107–193; Fig. 6) exist primarily at the periphery of the islands and in areas of exposed rock where there is little or no soil material to provide a potential obstruction for a contaminant to move vertically into the vadose zone. Bedrock formations that exhibit the highest vulnerability rates include the Geoffrey, De Courcy and Comox Formations (Figs. 1 and 2).

To identify the spatial changes between the traditional DRASTIC methodology and the modified DRASTIC-Fm approach, a version of the model was run without the Fm parameter (Fig. 7). Comparing Figs. 6 and 7, the overall impact of the presence of fault and fracture systems tends to augment the vulnerability of the regions within proximity to a structure. For example, the presence of faults and fractures within regions of low vulnerability increases the vulnerability range to moderately low. This is particularly evident on the central portion of Salt Spring where the presence of faults and fractures have augmented the vulnerability from moderately low (73–103) to moderate (103–133) and on Galiano and Gabriola islands where the vulnerability has been augmented from moderate (103–133) to moderately high (133–163).

Conclusions

A modified relative-index vulnerability mapping method is proposed for regional fracture aquifers, DRASTIC-Fm. The method encompasses the use of similar ratings and weights for hydrogeologic parameters used in the original US EPA DRASTIC methodology, but provides for an additional parameter that reflects a higher level of fracturing associated with bedding perpendicular joints, discrete fractures, fracture zones and faults. The features are rated according to their hydraulic influence on an aquifer system and their ability to transport contaminants directly into the subsurface.

Model outputs highlight regions of high vulnerability around island perimeters where the thickness of material above the aquifer is minimal, surrounding faults and fractures and in high recharge areas where topography changes. The fractured media parameter introduces an increased order of vulnerability to zones within proximity to known structures and provides a means of quantifying the potential impact of fracturing on the quality of a groundwater resource.

Although a comprehensive model, this model is a general representation of the hydrogeologic environment of the Gulf Islands. This methodology was chosen deliberately for its ability to be seamlessly adapted to other regions with similar hydrogeologic characteristics. Many of the datasets employed in the model are readily available or can be easily developed in most regions. Furthermore, the model outputs are represented in a manner that can be easily translated to support policy deliberations between hydrogeological professionals and land-use planners to integrate the model outputs into sustainable groundwater resource management strategies.

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