GEOLOGICAL SURVEY OF CANADA
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Technical Summary of Intrinsic Vulnerability Mapping Methods in the Regional Districts of Nanaimo and Cowichan Valley

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with
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EXECUTIVE SUMMARY

The Vancouver Island Region Watershed Protection Steering Committee initiated a collaborative project beginning in 2006 between the BC Ministry of Environment, Vancouver Island University, Natural Resources Canada, Vancouver Island Health Authority and Regional Districts on Vancouver Island to assess the relative vulnerability of the groundwater resources to contamination from surface sources. The need for this type of assessment was highlighted by increased development pressures coupled with industrial and agricultural land use activities that may threaten the quality of ground and surface water supplies. The vulnerability of aquifers to contamination needed to be characterized in order to be considered alongside other social, economic and environmental priorities for Vancouver Island and the province, as part of the comprehensive land use planning process.

The project team decided to develop “intrinsic aquifer vulnerability maps” as an initial phase of the project since this type of mapping has proven to be an efficient tool for assisting in decision-making by prioritizing regions of concern with respect to groundwater. Local governments, planners, and policy makers can use these maps to enable land-use decisions that take into consideration the sensitivity of the groundwater resources, encourage sustainable development, identify sensitive areas, plan monitoring strategies, and focus remediation efforts. An existing aquifer vulnerability methodology developed by the US Environmental Protection Agency, known as DRASTIC, was employed in the assessment. DRASTIC is an acronym for the seven parameters that can influence the vulnerability of a groundwater resource: D - Depth to water, R – (net) Recharge, A - Aquifer medium, S - Soil medium, T – Topography (slope), I - Impact of vadose zone and C – (hydraulic) Conductivity. These parameters are combined in an equation that is used to produce the resultant map that identifies areas of relative (higher and lower) vulnerability.

Several information sources were analyzed to create the aquifer vulnerability maps. Key datasets include the British Columbia Ministry of Environment’s application (WELLS) that comprises a database of water-well construction records and mapped aquifer delineations. Other important information sources include soil surveys, precipitation data, a digital elevation model and terrain classification. To address issues such as scope and consistent data coverage, the project team divided the Island by regional district boundaries to complete the intrinsic aquifer vulnerability assessment. Assessments for the regional districts of Nanaimo (RDN) and Cowichan Valley (CVRD) were completed and are discussed in this report. The assessments for these two regional districts also allowed the project team to fine-tune the assessment to the characteristics of Vancouver Island before the methodology is applied to the remainder of Vancouver Island. To ensure that the outputs of this project were relevant to decision-makers, staff from both the RDN and CVRD were involved in all stages of the project.

Results of the intrinsic aquifer vulnerability assessment for RDN and CVRD indicate that confined unconsolidated aquifers represent moderate to low intrinsic vulnerability due to the presence of a confining layer with low vadose zone permeability, combined with a slightly deeper depth to water. Unconfined, unconsolidated aquifers have a higher intrinsic vulnerability due to their relatively shallow depth to water, and permeable vadose zone and aquifer medium (reflected in the A and C parameters). Consolidated (i.e. bedrock) aquifers have a generally moderate to low intrinsic vulnerability due to their deeper depth to water, low permeability aquifer medium, conductivity, and vadose zone ratings.

This document details the methods used to produce intrinsic aquifer vulnerability maps for the RDN and CVRD study area, and may be used to update these maps in the future or guide the application of these methods to other areas of Vancouver Island.

ACKNOWLEDGEMENTS

The authors would like to thank the Regional District of Nanaimo, Cowichan Valley Regional District, First Nations band offices, and private companies for access to hydrogeological reports pertaining to the study area. Much of the data collection and compilation during the initial phase of the project and an early version of the DRASTIC analysis was completed by Regan Purdy and Lisa Munro of Vancouver Island University.

Thank you to the project working group for your participation during numerous meetings, for providing on-going feedback on the development of these maps, and for your contributions to this project. We thank Kevin Ronneseth of the BC Ministry of Environment for a detailed external review of the document and methodology which strengthened the final product. We appreciated comments from Gilles Wendling of GW Solutions who also reviewed this work and provided feedback based on his regional hydrogeological knowledge.

This project was sponsored by the Vancouver Island Region Watershed Protection Steering Committee and was funded by the BC Ministry of Environment, BC Ministry of Health, Vancouver Island Health Authority, Vancouver Island University, Natural Resources Canada, Regional District of Nanaimo, Cowichan Valley Regional District, and Living Rivers -Georgia Basin/Vancouver Island.

This project was inspired by the vision of Robin Gear of the Vancouver Island Health Authority, who was dedicated to improving protection for drinking water supplies. Although unable to see the completion of this project, Robin was a keen supporter and her legacy will persist as these maps are available to support decisions related to the protection of groundwater supplies. She is sadly missed.

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1.0 INTRODUCTION

In an area surrounded by ocean, with a multitude of lakes and rivers, and with abundant rainfall, there is a perception of unlimited water resources on Vancouver Island. However, increases in population, existing industrial and commercial land use practices, combined with the impacts of changing climate, may put the quality of water resources on Vancouver Island at risk. While the largest cities on Vancouver Island (Victoria, Nanaimo and Campbell River) all use surface water for their water supply, about 40 % of the Island's municipalities use groundwater for all or part of their water supply. In many suburban and rural areas, groundwater extracted from thousands of privately owned wells provides the only viable source of potable water. Groundwater is also crucial to the function of streams and wetlands. Sound water management practices and land use decisions are key factors in the protection of water quality. Land-use decisions are often made at the regional and local government levels with guidance from other agencies. In order to inform these management decisions, scientific research is needed; however, incorporating scientific information on water resources into ongoing planning, decision making, and policy development is challenging due to the complexity of water resource issues.

The Vancouver Island Watershed Protection Steering Committee, hereafter referred to as the 'steering committee', was formed in 2005 to work on coordinated, multi-agency approaches for water management on Vancouver Island and the Gulf Islands. This committee includes the Vancouver Island Health Authority (VIHA), the Office of the Provincial Health Officer and consists of representatives from many BC Ministries including Environment; Agriculture and Lands; Transportation and Infrastructure; Forests, Range & Housing; Community Services; Energy, Mines and Petroleum Resources; and Health. Health Canada, the Islands Trust, and the seven Vancouver Island Regional Districts are also involved in the steering committee. The steering committee recognized the need for land-use decision making tools to better protect the quality of the island's water resources; consequently, the steering committee spawned the collaborative Vancouver Island Water Resources Vulnerability Mapping Project (hereafter referred to as the 'VMP'), in 2006, with the BC Ministry of Environment (MoE), Vancouver Island University (VIU), Natural Resources Canada (NRCan), and VIHA to develop these groundwater protection decision making tools.

Aquifer vulnerability maps have proven to be an efficient tool for assisting decision-making since they identify regions of potential concern with respect to groundwater and indicate relative vulnerability (e.g. Piscopo 2001, Design Centre for Sustainability 2006, North Pender Island Local Trust Committee 2007). Local governments, planners, and policy makers can use vulnerability maps to aid sustainable development planning, identify sensitive areas, plan monitoring strategies, and focus remediation efforts (Aller et al. 1987, Van Stempvoort et al. 1992, Vrba and Zaporozec 1994).

Aquifer vulnerability is a commonly used term to refer to the environment's natural protection against groundwater contamination based on its physical characteristics (Foster 1987, Vrba and Zaporozec 1994, Bekesi and McConchie 2002). However, this term is sometimes used to describe not only the intrinsic characteristics of the system, but also the type, loading, transport and fate of a contaminant or group of contaminants that may be associated with various land use activities (i.e. hazards) (Focazio et al. 2002, Stigter et al. 2006). To reduce confusion, this report will use the term intrinsic aquifer vulnerability to describe the susceptibility of the groundwater system to contamination based on the natural (intrinsic) properties of the land, subsurface and groundwater flow system. This type of vulnerability assessment is a first step to assessing overall aquifer or groundwater risk, which also includes the potential hazards of land use activities and contaminants (Uricchio et al. 2004, Birkman 2006), and sometimes the consequence of losing the resource (Geological Survey of Ireland 1999, Birkman 2006), in addition to the intrinsic vulnerability of an aquifer.

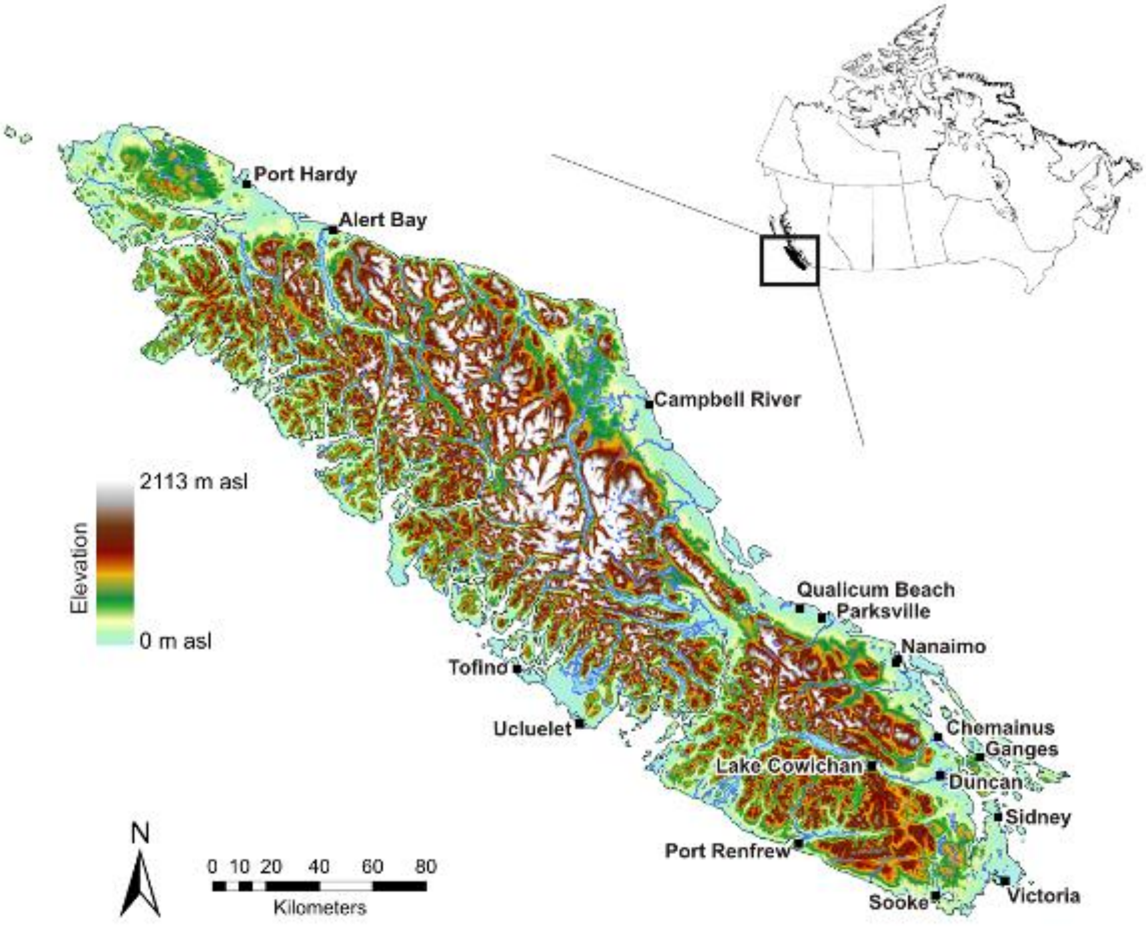
In this study we have examined the intrinsic aquifer vulnerability only. It should also be emphasized that aquifer vulnerability mapping is **not** a replacement for site specific investigations, nor should vulnerability maps be used as the sole basis for land use decisions (Aller et al. 1987, Van Stempvoort et al. 1992, Vrba and Zaporozec 1994).

Methods for characterizing intrinsic vulnerability vary from qualitative indexing (e.g. DRASTIC), to semi-quantitative measurements of resistance to flow (e.g. Aquifer Vulnerability Index (AVI)), to quantitative hydrogeologic assessments with numerical modelling (e.g. MODFLOW) (Focazio et al. 2002, Gogu and Dassargues 2000, Frind et al. 2006). For the current study, the DRASTIC method, developed by the United States Environmental Protection Agency (Aller et al. 1987), has been used to map the intrinsic vulnerability. DRASTIC is a regional, qualitative, indexing approach that has been used to map vulnerability in different aquifer systems around the world (e.g. Rosen 1994, Al-Zabet 2002, Vias et al. 2005, Gogu and Dassargues 2000, Stigter et al. 2006, Denny et al. 2007). This method assesses the relative intrinsic vulnerability of an area based on properties of the aquifer, overlying material, water table depth, topography, and recharge. The DRASTIC method was selected for use on Vancouver Island because it provides a regional assessment of vulnerability, is relatively easy to implement and understand, and uses readily available datasets.

2.0 STUDY AREA

Vancouver Island is located in south-western British Columbia (Figure 2.1) and is separated from the mainland by the Straits of Georgia, Johnston, Queen Charlotte, and Juan de Fuca. The island is over 450 kilometres (km) long, and up to 80 km wide, with an area of approximately 32 000 km^2. Vancouver Island mainly consists of mountainous terrain (Figure 2.1), with the ranges oriented southeast-northwest and with the highest peaks over 2 000 meters above sea level (m asl). The mountains grade to lowlands, mainly along the east coast of the island, where the majority of the island's population resides.

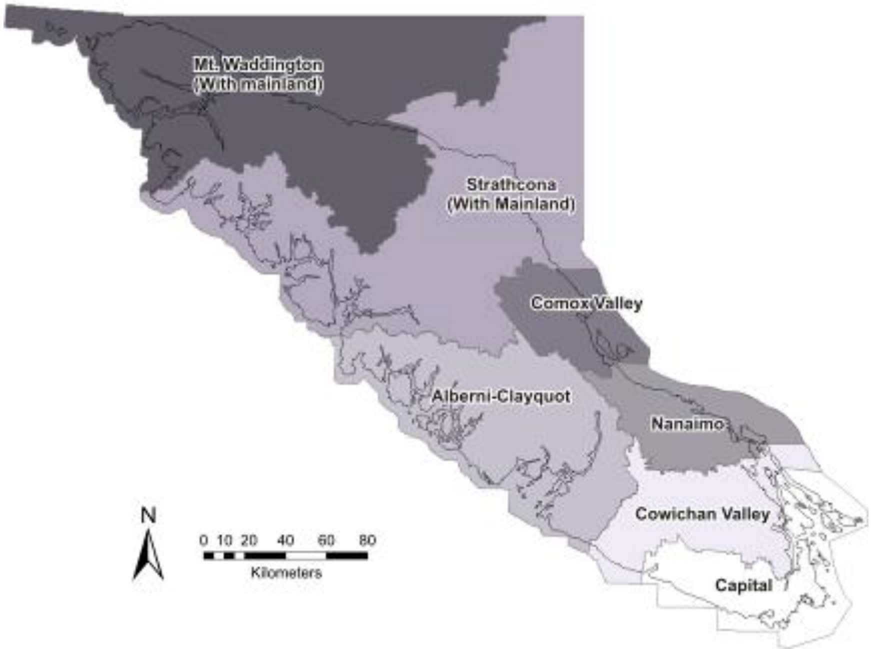
Figure 2.1 Topography of Vancouver Island with several municipalities.



The population on Vancouver Island was almost 764 000 in 2006, and is one of the fastest growing populations in the province, with a projected increase of over 30% by the year 2031 (Ministry of Labour and Citizens Services 2009). The island is divided into seven jurisdictional districts, all of which are included in the VMP, although only the Regional District of Nanaimo (RDN) and Cowichan Valley Regional District (CVRD) have been included in the first phase of this project (Figure 2.2). These two regional districts – hereafter referred to as the study area – are the initial focus of the mapping, with the project to be expanded to the other regional districts upon completion of this phase. Intrinsic vulnerability maps for the Gulf Islands have already been completed (Denny et al. 2007) and can be used in conjunction with the Vancouver Island map to provide comprehensive regional coverage.

Figure 2.2 Regional districts on Vancouver Island.

Note: area of interest for the first phase of this study is the Regional District of Nanaimo and Cowichan Valley Regional District.



2.1. Climate

Vancouver Island has a temperate rainforest climate with mild winters and cool to moderately warm summers. The orientation of the mountain ranges create very wet conditions along the west side of Vancouver Island, with drier conditions in the rain shadow along the east side. Average annual precipitation in Tofino (west coast) is ~3300 millimetres (mm), while in Nanaimo (east coast) is

~1200 mm, and in Victoria in the southeast is only ~900 mm (Environment Canada 2008). Temperatures are fairly consistent over most of the Island in the low lying areas, with an average annual temperature of ~10°C ranging between an average annual minimum and maximum of ~5°C and ~13°C (Environment Canada 2008).

2.2. Geology

The geologic history of Vancouver Island involves three major periods of volcanism, interspersed with periods of sediment accumulation (Yorath and Nasmith 1995). The region is part of the Insular Belt, which is the westernmost of five northwest trending sections of the Canadian Cordillera. Vancouver Island is primarily comprised of the Wrangellia Terrane, which initially formed far off the coast of ancient North America, and was accreted onto the continent beginning approximately 100 million years ago. In addition to the Wrangellia Terrane, Vancouver Island includes the Pacific Rim Terrane (extending along the west coast of the island from the Tofino area to Victoria) and the Crescent Terrane (extending from Sooke to Metchosin) plus the sedimentary rocks of the Nanaimo Group situated along the east coast of the island (Yorath and Nasmith 1995). Some of the Wrangellia Terrane rocks and most of the Pacific Rim Terrane rocks have been metamorphosed. Highlights of the complex geology of Vancouver Island are provided below, with reference to Yorath and Nasmith (1995).

The Devonian Period of the Paleozoic Era marked the beginning of the construction of Vancouver Island, around 380 million years ago. The Sicker Group (Duck Lake Formation (Fm), Nitinat Fm, and McLaughlin Fm), comprised of basaltic flows, pillow basalts, volcanic breccia, and tuffs, was formed during this time. From the Carboniferous to the Early Permian the sedimentary rocks of the Buttle Lake Group were deposited as the volcanic arc was eroded to a flat, submarine plateau. This group consists of limestone, chert, and argillite as well as some pillow basalts and tuffs (Fourth Lake Fm, Fourth Lake Volcanics, Mount Mark Fm, Nanoose Complex, St. Mary's Lake Fm).

After a period of uplift and erosion from the Late Permian to the Early Triassic, the sedimentary rocks of the Vancouver Group were deposited in the Mid to Late Triassic. These rocks consist of shale, siltstone, limestone, and various argillites (Daonella Beds, Quatsino Fm, Parson Bay Fm), but are dominated by basaltic volcanics (Karmutsen Fm). The Karmutsen Fm is the thickest and most widespread unit on Vancouver Island (Yorath and Nasmith 1995). The West Coast Crystalline Complex, a set of intrusive igneous rock including the Mount Hall Gabbro, was also formed during the Late Triassic.

In the Early Jurassic, the volcanic rocks (mainly tuffs) of the Bonanza Group were formed, along with coeval intrusive diorite and granodiorite of the Island Plutonic Suite. Beginning in the mid Cretaceous, Wrangellia began to collide with the western edge of North America. In the Late Cretaceous, the various sedimentary formations of the Nanaimo Group were deposited. This series of interbedded mudstone, siltstone, sandstone, and conglomerate dominates on the Gulf Islands and the eastern margin of southern Vancouver Island. Twelve formations are included in the Nanaimo group and are typically interbedded but dominated by either mudstone/siltstone or sandstone/conglomerate (Mackie 2002, CPAWS 2005).

Moving into the Cenezoic Era, the Tertiary Period was dominated by the emplacement of igneous intrusions and volcanics of the Metchosin Igneous Complex, Clayquot Plutonic Suite, Catface Intrusions, Flores Volcanics, and Alert Bay Volcanics, with mainly mafic compositions.

During the Pleistocene Epoch of the Quaternary Period, Vancouver Island was affected by at least three glaciations. Sediments from the Pleistocene include the glacio-fluvial sands of the Quadra Sands and the glacial tills of the Vashon Drift (Fyles 1963, Clague 1977). Younger Holocene deposits consist of marine, fluvial, and lacustrine deposits relating to prior sea levels called the Capilano Sediments as well as the Salish sediments, relating to deposits during present sea level (Fyles 1963). These Quaternary deposits are up to several tens of metres thick in places.

2.3. Hydrogeology

Developed aquifers in BC have been mapped with the BC Aquifer Classification System (Kreye et al. 1994). Aquifer boundaries have been defined based on bedrock and surficial geology mapping, well lithology records, and hydrogeological reports. The system classifies aquifers based on their level of development and intrinsic vulnerability to contamination (Berardinucci and Ronneseth 2002). The vulnerability to contamination classification is derived from the depth to water and permeability and thickness of overlying sediments. These parameters are evaluated over the mapped aquifer as a whole, and assigned one of three vulnerability categories (A - High, B - Medium, C - Low).

There are over 200 mapped aquifers on Vancouver Island (BC MoE, WELLS application). These aquifers consist of either fractured bedrock or unconsolidated (surficial) sediments. The most productive aquifers are within thick sand and gravel glacial outwash and post-glacial fluvial deposits. Wells completed in major faults or fractures in bedrock can also yield very high quantities of water (Yorath et al. 2002). Unconfined sand and gravel aquifers are most vulnerable to contamination since many have a shallow depth to water table, high vadose zone, and high aquifer permeability (Denny et al. 2007). Additionally, an often high level of development may create a hazard threat in these areas of unconfined aquifers.

The aquifers of Vancouver Island and the Gulf Islands (off south-eastern Vancouver Island) provide water to many of the smaller communities and to most residents of rural areas. Many major centres, including Victoria and Nanaimo use surface water from upland watersheds. Research on climate change in the Georgia Basin, which includes southern Vancouver Island, has shown a warming pattern which will affect precipitation patterns, leading to wetter winters and drier summers (Rodenhuis et al. 2007). This anticipated climate change will likely affect surface water supplies and recharge to the aquifers on Vancouver Island.

There are over 24 000 wells on Vancouver Island according to the BC WELLS application (as of January 15, 2008), representing about 30% of all the reported wells in the province. Nearly half of the wells on Vancouver Island are located in the study area. These wells provide important geologic and hydrogeologic data such as lithology, water level and well yield. However, only a portion of wells (sometimes less than 20%) in a given area tend to be captured by the database since submission of well construction reports has been voluntary.

Previous work on the Gulf Islands (Mackie 2002, Surrette et al. 2008), has shown three main hydrostructural domains through the Nanaimo Group bedrock that form most of the Gulf Islands: fault and fracture zones (areas of greater fracture intensity close to major faults and fractures), highly fractured interbedded mudstone and sandstone, and less fractured sandstone. Of these domains, it is the fault and fracture zones and interbedded mudstones and sandstones that appear to be the most transmissive (Surrette et al. 2008). Intrinsic vulnerability maps have been completed for the Gulf Islands using the DRASTIC-Fm approach (Denny et al. 2007), which incorporated the role of fractures into the vulnerability assessment. It is not clear if the Nanaimo Group rocks found on Vancouver Island behave in the same manner as the Gulf Islands, although their relative proximity to the Gulf Islands suggests this possibility. A detailed fracture study would be needed to verify this.

3.0 DRASTIC

The DRASTIC method (Aller et al. 1987) has been used to map the regional intrinsic aquifer vulnerability of the RDN and CVRD study area. This indexing method provides a relative, qualitative assessment of the intrinsic vulnerability of an aquifer to contamination. The assumptions in this method are that a) the contaminant is introduced at the surface, b) that it is driven vertically through the vadose zone (between the soil and the water table) by precipitation at the same rate as water, and c) that the mapping extent is 100 acres (40.4 hectares) or larger. This minimum mapping extent is to emphasize the regional nature of this vulnerability mapping method.

DRASTIC stands for each of the seven input parameters: ***D***epth to water, net ***R***echarge, ***A***quifer medium[1], ***S***oil medium[1], ***T***opography, ***I***mpact of the vadose zone, and hydraulic ***C***onductivity (Table 3.1). Each parameter is mapped and attributes are assigned a rating from 1 to 10 (lowest to highest vulnerability) based on a set of rating tables. The final vulnerability is calculated by summing the product of each parameter's rating and a relative fixed weight (Equation 3.1 – DRASTIC parameter weights).

$$5D + 4R + 3A + 2S + 1T + 5I + 3C = \text{intrinsic vulnerability} \qquad (3.1)$$

The final vulnerability is represented by a value ranging between 23 and 230. Different parameter weights are assigned if the vulnerability map is completed in an area where pesticides are a concern (Aller et al. 1987). Denny et al. (2007) added a fractured media parameter to the DRASTIC methodology to incorporate the impact of discreet fracture flow on vulnerability (Table 3.1). The use of the fractured media parameter on Vancouver Island is discussed in Section 5.9.

The DRASTIC methodology differs from the vulnerability rating of the BC Aquifer Classification System in a number of ways. DRASTIC includes more parameters (e.g. aquifer medium, recharge), and more spatial variability of parameters within mapped aquifers. Rather than assigning a single vulnerability value to an entire aquifer polygon, DRASTIC may show variation in the vulnerability as parameters such as depth to water, topography, soil medium, and impact of the vadose zone vary over a single aquifer. Another difference is that DRASTIC only shows the vulnerability to the uppermost aquifer, whereas the BC aquifer Classification system can show the vulnerability of a number of aquifers

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[1] The *A* and *S* parameters in the original DRASTIC documentation (Aller et al. 1987) are called 'aquifer media' and 'soil media'. As both the aquifer and soil are considered and rated as a whole within the DRASTIC methodology, the singular 'aquifer medium' and 'soil medium' are used in this document to refer to these parameters.

that are stacked on top of each other. In this case the lower aquifers are less vulnerable since contaminants have further to travel and are protected by the overlying sediment. For these reasons, the vulnerability produced from the DRASTIC methodology may be different from the vulnerability classification assigned to previously mapped aquifers in BC.

Table 3.1 DRASTIC parameter summary

	Parameter	**Impact on intrinsic aquifer vulnerability**	**Weight***
D	Depth to water	As water depth decreases, vulnerability increases, due to shorter transport time between the surface and the aquifer, and less time for natural attenuation	5
R	Recharge	Greater recharge promotes faster downward contaminant movement; therefore, the higher the vulnerability	4
A	Aquifer medium	In general, larger grain sizes and more intense fracturing lead to a higher vulnerability because of increased permeability and decreased natural attenuation potential	3
S	Soil medium	Areas with thin coarse textured soils will have a higher vulnerability than thick fine grained materials, such as silts, which have slower infiltration and a higher natural attenuation capacity	2
T	Topography (slope)	Represented by the slope. The lower the slope, the higher the vulnerability due to less runoff and a higher potential for infiltration of contaminants into the subsurface	1
I	Impact of vadose zone	A higher permeability of the vadose zone material leads to a higher vulnerability, due to decreased time for natural attenuation of any contaminants	5
C	(hydraulic) Conductivity	The faster water and contaminants can move through an aquifer unit, the greater the likelihood of the contaminant spreading throughout the aquifer; therefore, the higher the hydraulic conductivity of an aquifer the higher the vulnerability	3
Fm	Fractured Media (Denny et al. 2007)	The vulnerability of a discreet fracture is a combination of the orientation of the fracture to the direction of principal regional stress, the fracture length, and the fracture intensity	3

*5D + 4R + 3A +2S + 1T + 5I + 3C = intrinsic aquifer vulnerability (regular weightings)

4.0 DATA SOURCES

Data were collected from many different sources and at many different scales for use throughout this study (Table 4.1). Data from both the BC WELLS application and the hydrogeological reports required significant effort to prepare these data for use in the intrinsic vulnerability analysis.

4.1. British Columbia WELLS Application

The database in the BC MoE WELLS application contains the records of over 93 000 wells drilled in BC from 1900 onward, of which about 81 000 are spatially located. A subset of the wells on Vancouver Island located within the study area was extracted from the WELLS database. A Microsoft Access® version of the WELLS database (developed by M. Toews and D. Allen of Simon Fraser University, 2007) was used for this study. It was updated with well information from the provincial database as of January 15, 2008. This Access® version of the WELLS database was used to link the well attributes to the well locations in the geographic information system (GIS) and for ease of working with the database on a regional scale. The well information within this database is used to determine the depth to water parameter and lithology; this information is a factor when evaluating the D (depth to water), A (aquifer medium) and I (impact of the vadose zone) parameters.

At the outset of the project, well records without a spatial location within the study area were located. This location process involved obtaining original well records (paper copies) from the MoE, and using the online RDN cadastral mapping tool, the online BC imap, online BC Assessment Authority data, and a digital cadastral map provided by the CVRD to identify the centre of each land lot and assign corresponding UTM coordinates for each well. Over 1 300 wells in the study area were located using this methodology. Wells unable to be located were returned to the MoE. Upon locating these wells, the WELLS database was used to match the newly located wells to well records that may have already existed in the WELLS database. If a corresponding well record was found in the WELLS database, the location information was updated; otherwise, the paper well record was returned to the MoE to be entered into the database as a new well.

Preparing the WELLS database for use in the *D*, *A*, and *I* parameters also required considerable effort. The database contains wells constructed in different years and seasons, with different data quality, and with a varying amount of information for each well since the requirement for drillers to submit full lithological reports with a well is recent. Additionally, many errors were found in the study area portion of the database, including both localized errors and systemic, database-wide errors.

Table 4.1 Data sources for vulnerability mapping in the study area.

D = depth to water, R = recharge, A = aquifer medium, S = soil medium, T = topography, I = impact of the vadose zone, C = conductivity, FM = fractured media

Data Set	Source	Scale	Date	Description	Use in DRASTIC
Digital Elevation Model	BC Integrated Land Management Bureau	25m grid	Gridded in 2002 (1968-2002 data)	Digital elevation model of the study area	*D*, *T*, visual
Wells	BC WELLS application	N/A	Jan 2008	Wells from BC database, in MS access database	*D*, *I*, *FM*, *C*, *A*
Rivers	BCGS geology map data	1:50K	2005	Rivers of Vancouver Island	*D*, visual
Lakes	BC watershed atlas	1:50K	2005	Lakes of Vancouver Island	*D*, visual
Bedrock geology maps	BCGS and GSC	1:250K (BCGS), 1:50K (GSC)	2005	Compilation of BCGS bedrock geology map of Vancouver Island (Massey et al. 2005) and a more detailed geology map of southeast Vancouver Island compiled by M. Journeay (GSC, unpublished)	*A*, *C*, *I*
Precipitation	ClimateBC	400m grid	2006	Interpolated precipitation data for Vancouver Island	*R*
Aquifer polygons & worksheets	BC WELLS application	N/A	2007 (polygons) 1995-2004 (worksheets)	Mapped aquifer polygons and aquifer worksheets	*A*, *C*, *I*
Hydrogeological consulting reports	Various	N/A	1963-2007	71 reports on RDN and CVRD areas. Relevant hydrogeologic data was extracted from these reports.	*C*
Soil survey	1) BC44 (Jungen 1985) 2) BC43-4 (Kenney et al. 1989) 3) CAPAMP Vanc Is	1) 1:100K 2)1:20K 3) 1:20K	1) 1985 2)1989 3) 1985-89	1,2) National Soils Database detailed soil surveys with soil texture and drainage. 3) BC CAPAMP soil surveys - only available for valley bottom/low lying areas.	*S*
Terrain map	Forest Renewal BC	1:50K	1975-1983	Compilation of terrain mapping of Vancouver Island. Texture included in long code, sometimes drainage is available depending on the level of map detail	*I*
Lineaments	NRCan (unpublished)	N/A	2004	Lineaments found in analysis of LANDSAT imagery of southern Vancouver Island	*FM*
Regional boundaries	RDs and MoE	N/A	N/A	Regional boundaries of RDN and CVRD, including electoral districts.	Visual

A general problem with the data in WELLS was non-populated fields. For example, in some cases, the “bedrock depth” field was blank even though bedrock was encountered during drilling, as identified on the lithology log. Over 1000 wells in the study area were found to have this error, which hindered automatic sorting of bedrock wells from surficial wells. To populate bedrock depth in the appropriate field, a query was set up in the Microsoft Access® database to search for well records without a bedrock depth entered, but which indicated the presence of bedrock in the lithology log and mappable unit BC field (the edited lithology with standard terminology). The key words used were “bedrock”, “sandstone”, “shale”, “granite”, “limestone”, and “other sedimentary”. These wells were then assigned the appropriate bedrock depth manually after examining the lithology log for each well and determining at what depth bedrock was encountered.

Erroneous depths were recorded in the “bedrock depth” field in approximately 200 wells. These erroneous bedrock depths included wells that had been deepened (i.e. log showed “previously drilled”) where the bedrock depth was entered as the starting depth of the deepened well. An example of this is for a log showing 0 to 50ft “previously drilled”, and 50ft to 75ft of granite, the bedrock depth would be entered as 50ft. It is unclear if this is the actual bedrock depth, or if bedrock was encountered in the previous drilling of the well. In these cases, the bedrock depth field was cleared, and the well tag number – a unique well identifier in the WELLS database – recorded to indicate that the well is in bedrock, but with an unidentifiable bedrock depth.

Another localized bedrock error was where the bedrock depth was defined incorrectly. For this study, the top of any “weathered bedrock” was considered to be the bedrock surface, and a few well records were changed accordingly. A third type of localized bedrock error was encountered in 160 deep wells (~50m to 250m deep) where depths to bedrock were very deep, near the bottom of the well; however, the lithology log showed bedrock depth as very shallow. It appears the bedrock depth field was populated with the bedrock thickness (i.e. from start of bedrock down to bottom of well), rather than the depth from ground surface to bedrock. The bedrock depths for these wells were manually corrected.

In all of the above cases it is assumed that the lithology log is more accurate than the “bedrock depth” field. This is a reasonable assumption because mapping the bedrock depth prior to any fixes in the database clearly showed areas where the bedrock was inconsistent with all the other wells around it.

Other WELLS database errors included localized errors in well depth or water depth (e.g. unreasonable well depths, such as 34 000 ft., or water depths greater than well depths). Though the above queries and manual examination of the WELLS database captured many errors, there are still likely other errors that have not been identified by this analysis.

4.2. Hydrogeological Report Compilation

Hydrogeological reports were collected to provide hydraulic properties for the *C* parameter and to create a database of all hydrogeological reports related to the study area. This document discusses only the work relating to the evaluation of the *C* parameter. Some of the hydrogeological reports were also used for verification to compare to the vulnerability map to ensure the vulnerability was captured accurately in those areas.

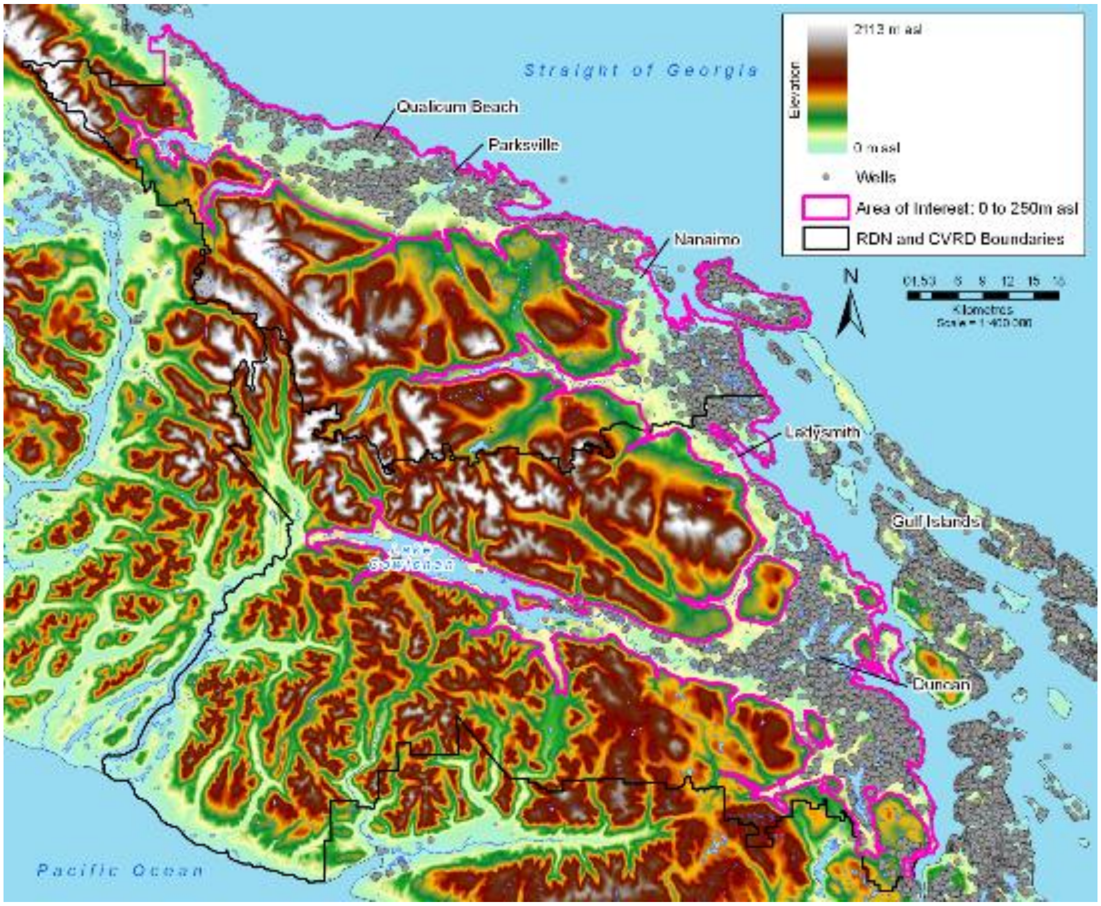
Well completion reports, pumping test reports, water supply studies, and other hydrogeological reports were collected from the RDN and CVRD regional district offices, other local government offices (e.g. Qualicum Beach), private companies, MoE offices, ECOCAT and First Nations band offices. These reports were reviewed to extract well location, lithology, completion information, well yield, specific capacity, transmissivity, and hydraulic conductivity. Hydraulic data was compiled from 32 reports for the RDN and 39 reports for the CVRD, although it is likely that more reports exist for these areas. The studies range in date from 1963 to 2007. Unfortunately, hydraulic conductivity was only reported in one report, although many reports contained values of transmissivity (T) and/or specific capacity (SC). Some reports have actual pumping test data, including time-drawdown data. Re-analysis of these tests using comparable methods may be useful for more accurately characterising the distribution of hydraulic conductivity in the study area resulting in a more accurate *C* parameter, but was not within the scope of this study.

The wells in each report were referenced to the aquifer they were completed in. All hydrogeological reports were scanned and forwarded to the MoE to be added to ECOCAT, the MoE’s public online reports catalogue, with consent from the report owner(s).

5.0 METHODS

The original area of interest for this study was the entire RDN and CVRD (including associated municipalities) (Figure 5.1). While data are available for the *R*, *A*, *S*, *T*, *I*, and *C* parameters throughout this area, there is a lack of well data in the upland, mountainous areas (Figure 5.1). This lack of data meant that the depth to water parameter could not be interpolated throughout the entire study area. Consequently, the final mapping extent includes all areas below 250 m asl, which encompasses most of the wells in the study area. Additionally, most areas under development, or already developed, lie below this elevation. For the *R*, *A*, *S*, *T*, *I*, and *C* parameters, the maps are shown over the entire RDN and CVRD area. As more well data becomes available, it may be possible to extend the *D* parameter beyond the 250 m asl boundary.

Figure 5.1 Well distribution and area of interest for intrinsic vulnerability mapping in the Regional District of Nanaimo and Cowichan Valley Regional District.



5.1. Aquifer Delineation

The methods used to identify the aquifers of interest in the study area are described first since this forms the basic conceptual hydrogeological model for the intrinsic vulnerability maps. Additionally, some of the DRASTIC parameters depend on the aquifer of interest being defined prior to their analysis.

The DRASTIC map of the study area represents the intrinsic vulnerability of the main uppermost aquifer to contamination (i.e. does not consider the vulnerability of lower aquifers in layered systems, or perched water tables). Different approaches were used to determine the upper aquifer of interest depending on the availability of mapped aquifer polygons, and the well distribution (Figure 5.2). For this project, a ‘mapped’ aquifer refers to an aquifer delineated by the BC Aquifer Classification System and ‘unmapped’ aquifers are located outside these areas. Unmapped areas may contain potential aquifers that have not been delineated and, as a result could be referred to as ‘potential unmapped aquifers’. For the purposes of this report, all such areas will be referred to as ‘unmapped’ aquifers. Additionally, unconsolidated material is referred to as ‘surficial’ deposits, and consolidated material is referred to as ‘bedrock’.

Six types of aquifers were recognised for this study (Figure 5.2, Figure 5.3):

A. Mapped surficial, unconfined aquifers
B. Mapped surficial, partially confined aquifers
C. Mapped surficial, confined aquifers
D. Mapped bedrock aquifers
E. Unmapped surficial aquifers
F. Unmapped bedrock aquifers

In the areas of stacked aquifers mapped by the BC Aquifer Classification System, surficial unconfined aquifers were selected as uppermost. Where there were no mapped surficial unconfined aquifers present, surficial partially confined or confined aquifers, followed by bedrock aquifers were selected. If an area has a mapped, confined surficial aquifer overlying a mapped bedrock aquifer, then the confined surficial aquifer was selected as uppermost. The level of confinement of mapped aquifers was determined from the aquifer worksheets, and was either unconfined, partially confined or confined. Aquifers deemed to be partially confined were overlain by a discontinuous confining layer. All mapped aquifers determined to be uppermost are shown in Figure 5.3. Most of the area below 250 m asl is covered by mapped aquifers, however there are some areas that have not been mapped by the BC Aquifer Classification System.

There are instances where shallow, likely dug, wells tap into small pockets of water bearing material above the main aquifer. Where the main uppermost aquifer is mapped either surficial confined or bedrock, the vulnerability of any overlying water-bearing material is not assessed in this study. The vulnerability map corresponds with the main uppermost aquifers shown in Figure 5.3.

Figure 5.2 Identification process to determine the uppermost aquifer.

Note: ‘Mapped’ aquifers refer to those mapped with the BC Aquifer Classification System, and ‘unmapped’ refers to all other areas.

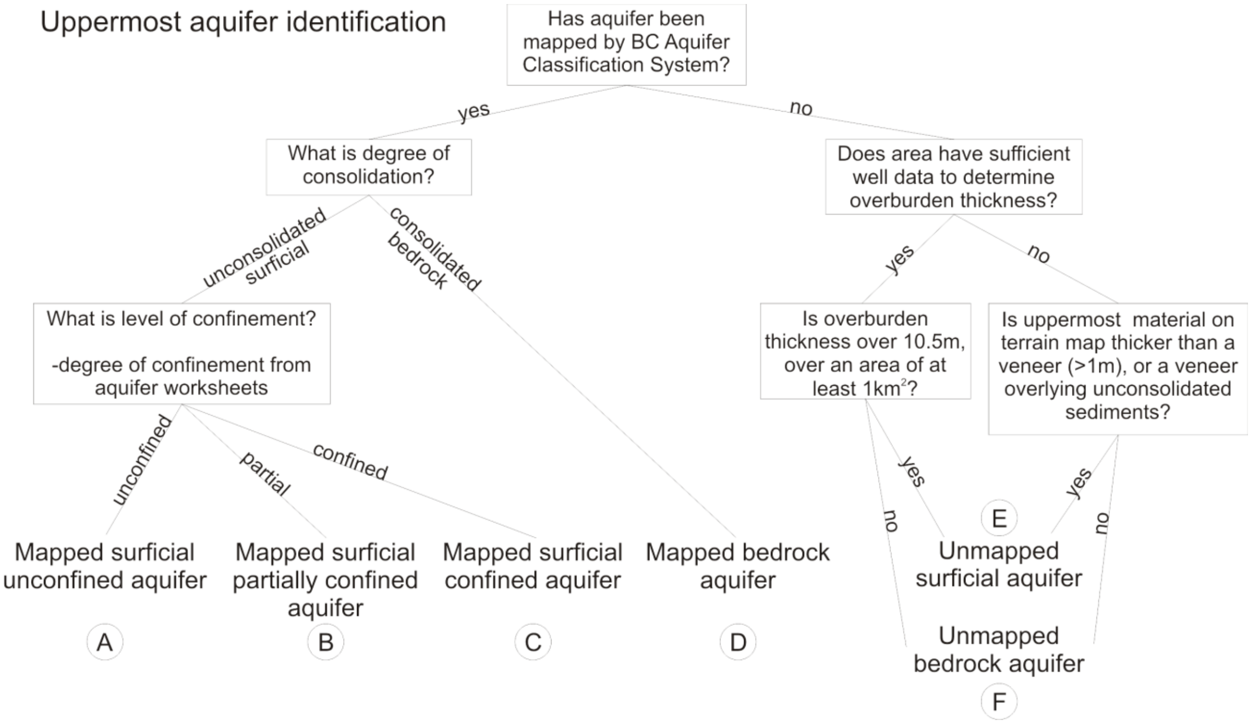
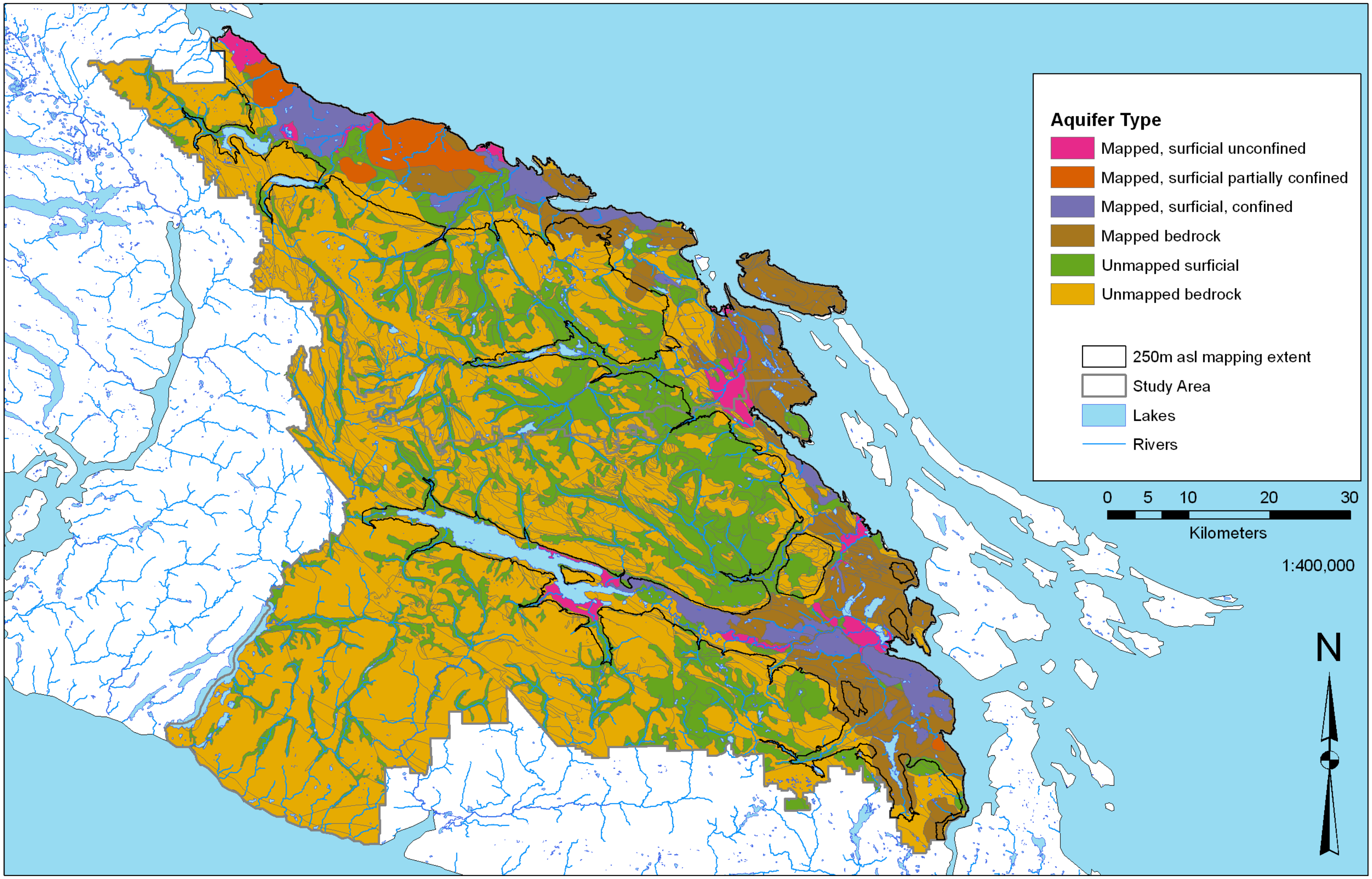


Figure 5.3 Aquifer types within the Regional District of Nanaimo and Cowichan Valley Regional District. 'Mapped' aquifers refer to those mapped with the BC Aquifer Classification System, and 'unmapped' refers to areas outside those with mapped aquifers.



In areas of unmapped aquifers, two approaches were taken to define the aquifer extent (Figure 5.2). In areas without mapped aquifers, but with well coverage, overburden thickness was used to determine if the most likely uppermost aquifer was surficial material or bedrock. An overburden thickness map was created by interpolating all recorded bedrock depths from the WELLS database, and shows the thickness of unconsolidated material overlying bedrock. Aquifers in the unmapped areas were determined based on the thickness of overlying unconsolidated material: where the overburden is thick, there is a high probability that the uppermost aquifer will lie in the surficial deposits (i.e. the overburden); but where the overburden is thin, the uppermost aquifer is likely in the bedrock.

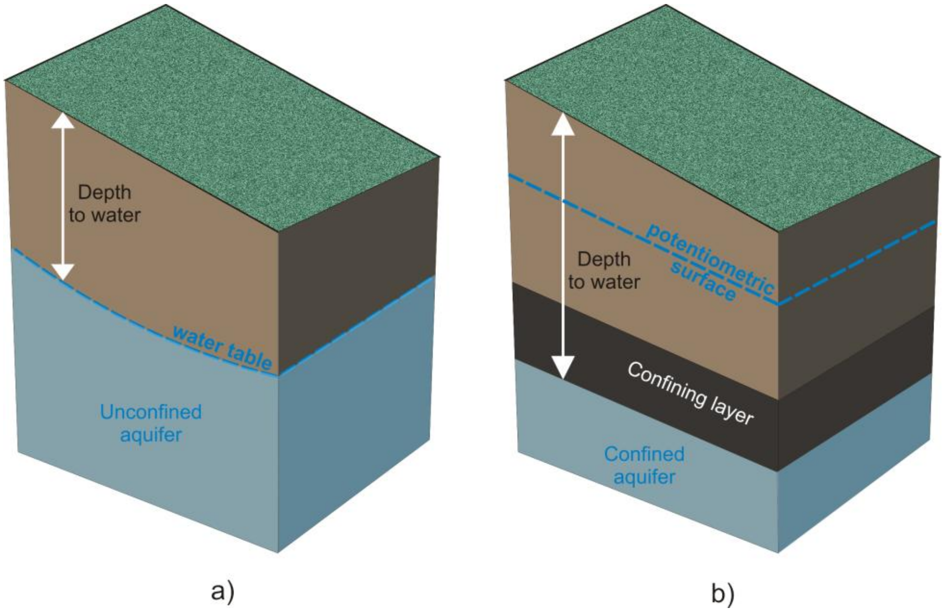
To determine the critical overburden thickness capable of supporting a surficial aquifer in the study area, the overburden thickness in areas of mapped aquifers was examined to estimate the minimum thickness that would be considered a surficial aquifer. The threshold was varied to optimize the classification of wells in both bedrock and surficial mapped aquifers. The optimum thickness was found to be 10.5 m, when 82% of both bedrock and surficial wells were correctly identified in all mapped aquifers. Many of those wells incorrectly identified were located close to a mapped aquifer boundary, and when a buffer zone of 200 metres (m) around each mapped aquifer was included, it increased the number of correctly classified wells to more than 90%. In addition, it was also assumed that the minimum aquifer size was 1 km^2, based on the minimum size of the mapped aquifers in the study area, which in turn was based on the availability of well data.

Finally, in areas without either mapped aquifer polygons or wells, the surface expression portion of the terrain map code was utilized to identify the most likely uppermost aquifer (Figure 5.2). Although the critical overburden thickness was determined to be 10.5m, the terrain maps do not report thickness of overburden sediments. The only thickness information given is the difference between a veneer (<1m) and a blanket (>1m). Bedrock aquifers were identified in areas with a veneer of sediment (<1m thick), underlain by rock, or just rock, which were usually at higher elevation. The remaining areas, mainly in the valley bottoms, were identified as surficial aquifers as thicker blankets of unconsolidated sediment can be found there (Figure 5.3). Future well records will verify both the existence of an aquifer and its vulnerability (i.e., DRASTIC index value).

5.2. Depth to Water

The deeper the water table (the depth where subsurface is fully saturated), the longer it will take contaminants to reach an unconfined aquifer (Figure 5.4), allowing more time for natural attenuation and lowering the vulnerability (Aller et al. 1987). If the uppermost aquifer is confined, the depth to water parameter is represented by the depth to top of aquifer (Aller et al. 1987) rather than the potentiometric surface (Figure 5.4) since the top of the aquifer is where a contaminant would physically enter the aquifer. The depth to water parameter was determined for the uppermost aquifer in the study area. Water levels and top of aquifer depths were selected from the WELLS application, depending if the uppermost aquifer was unconfined or confined, and the depth to water surface was interpolated for the study area. Due to the distribution of wells, the interpolation was limited to areas below 250 m asl. The depth to water parameter was the limiting dataset for the extent of the final vulnerability map.

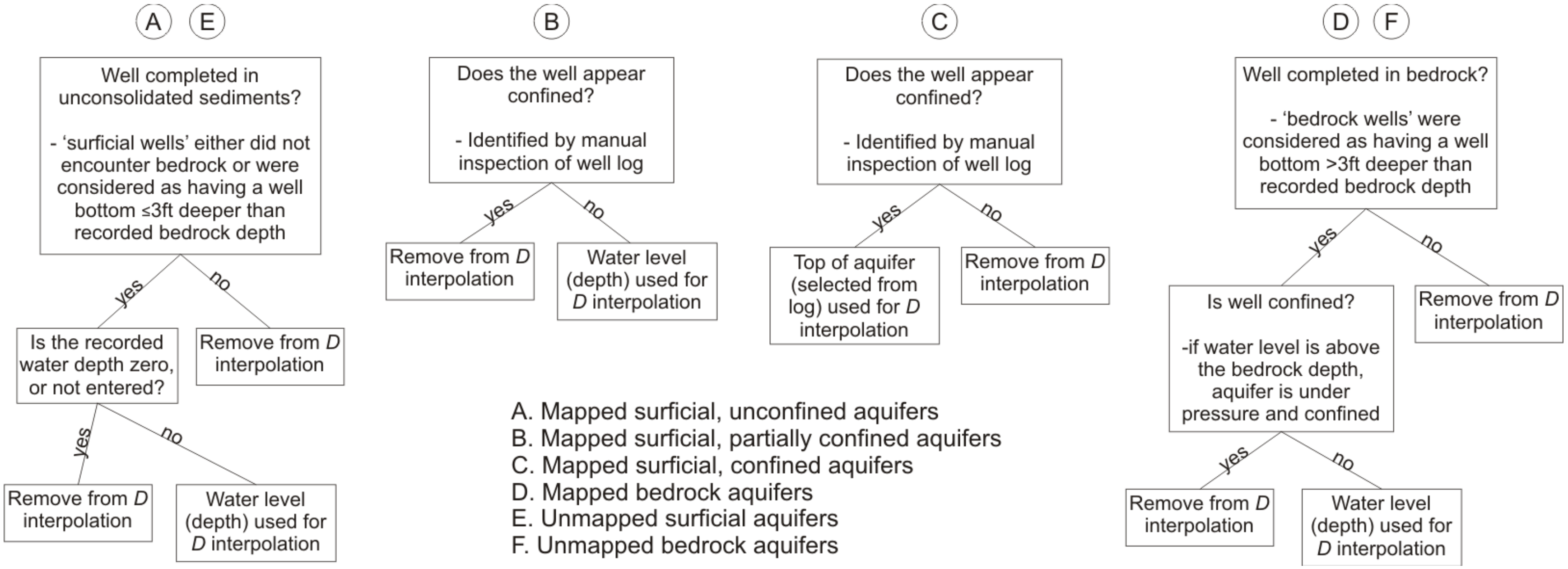
Figure 5.4 Depth to water parameter in a) an unconfined aquifer, and b) a confined aquifer



The WELLS application cannot be used directly to determine the depth to water parameter over a large region such as the RDN and CVRD. Multiple types of stacked aquifers are found within the study area and wells in any one area are not always completed in a single, common aquifer. Therefore, recorded water levels may represent the water table or potentiometric surface of many aquifers: wells can be drilled through multiple aquifers into a lower confined aquifer, and dug wells may capture a local, unmapped, perched water table above a larger aquifer. In order to map the depth to water parameter, wells were selected that were completed in the identified uppermost aquifers.

Wells were processed based on their suitability for interpolating the depth to water of the uppermost aquifer (Figure 5.5). Once the six types of aquifers of interest were identified (Section 5.1), the well records were reviewed to identify which wells fit the properties of the aquifer (Figure 5.5). For example, if the uppermost aquifer was a surficial unconfined aquifer, all wells completed in bedrock within that aquifer's boundaries were removed. For this study, a bedrock well was defined when the well depth was greater than three feet below the bedrock surface. This definition was used because many wells in the area encountered bedrock, but only at the very bottom of the well (i.e. drilling stopped upon hitting bedrock).

Figure 5.5 Methods for selecting wells for mapping the depth to water parameter in each of the six aquifer types



Mapped surficial unconfined aquifers

The depth to water recorded in the WELLS database was used in the *D* parameter after removing any bedrock wells, wells with no recorded water depth, or wells with a recorded water depth of zero. Also, in areas where these aquifers were overlying mapped, surficial, confined aquifers, wells were manually inspected to remove those wells completed in the lower aquifer.

Mapped surficial, partially confined and confined aquifers

In areas of mapped surficial, confined and partially confined aquifers, the depth to top of aquifer was manually selected for each well. All well logs were reviewed, including those without water levels and bedrock wells. Wells were identified as unconfined, confined, or unknown, along with any special properties (e.g. no water depth, previously drilled well). For confined wells, the depth to top of aquifer was selected as follows:

- Confining layers generally consisted of clay, till, hardpan, and silt. Silty gravels and silty sands were sometimes considered confining, and sometimes permeable, depending on the aquifer. The degree of permeability assumed depended on the aquifer description from the aquifer worksheets, the water level, other lithologies in that well and wells nearby, and driller’s comments.
- Many wells were drilled through multiple layers of high and low permeability material. In this case, if upper water bearing units were noted, but the well was drilled deeper, the upper unit was selected as the aquifer since it represents the first encountered water. If no upper water bearing units were identified, then the aquifer was assumed to be the water bearing unit near the bottom of the well (as an open hole or where the screen is likely placed).
- No explicit minimum confining layer thickness was used, although thin layers of low permeability material were considered confining if the water level in the well rose above these low permeable layers (i.e. likely due to artesian pressure)
- Well records were assigned a code describing any special properties that would help delineate the *D* parameter or to account for why the well record was not included.
    - L – No lithology log
    - B – Bedrock well (drilled below surficial aquifer)
    - Z – No reported water depth, zero water depth (i.e. do not know if water level is at surface, well is flowing, or water level was not recorded)
    - D – Deep well in lower aquifer
    - O – Well constructed in an unconfined aquifer overlying a deeper confined aquifer
    - C – Confined well in a partially confined aquifer
    - S – Surficial (unconsolidated) well constructed over an identified bedrock aquifer

    - U – Confining layer unknown, cannot identify confining layer or aquifer from log
    - A – Artesian well (flowing)
    - N – Lithology described, but no depths
    - R – Repeated well (two well entries for one well)
    - P – Previously drilled bedrock well, lithology is missing for upper layers
    - E – Erroneous depths (i.e. 3500m)
- In some wells, there is an apparent confining layer (e.g., clay), but the driller reports “dry” aquifer material below the confining layer, and then “wet” aquifer material. Although it appears that the possible confined aquifer is not fully saturated, the depth to the top of aquifer, rather than the water level, was selected to provide a conservative depth to water.

For partially confined aquifers, only those wells found to be unconfined were used to produce depth to water. This is a conservative approach for mapping the depth to water since the water table, once interpolated across the aquifer, is likely shallower than the depth to the top of aquifer.

For confined aquifers, only those wells found to be confined were used to produce the depth to water surface from the depth to top of aquifer selected for each well.

Unmapped surficial aquifers

All unmapped surficial aquifers were assumed to be unconfined. This represents a conservative approach to the vulnerability of these areas. If the aquifer is confined, the vulnerability will be lowered by a low permeability vadose zone and aquifer medium. Additionally, there are few wells in these areas with which to identify the level of confinement of these aquifers.

Mapped and unmapped bedrock aquifers

All bedrock aquifers (mapped and unmapped) were considered partially confined. The aquifer worksheets for the mapped bedrock aquifers indicated varying thicknesses of discontinuous unconsolidated overburden over a majority of the aquifers. Some of the overburden was comprised of confining silt and clay. For these reasons it was decided to map all bedrock aquifers as partially confined (Figure 5.5). Using a simple calculation within the well database, wells with a water level greater than three feet above the bedrock surface were considered confined and removed from the analysis. The remaining wells, with reported water levels below the depth to bedrock, were assumed to be unconfined and these water levels were used to map the depth to water. It is possible that some of the wells assumed to be unconfined are actually protected by a confining layer of fine grained (i.e. clay-bearing) drift. This property would be captured in the impact of the vadose zone parameter, and would be reflected by a lower vulnerability rating in those areas.

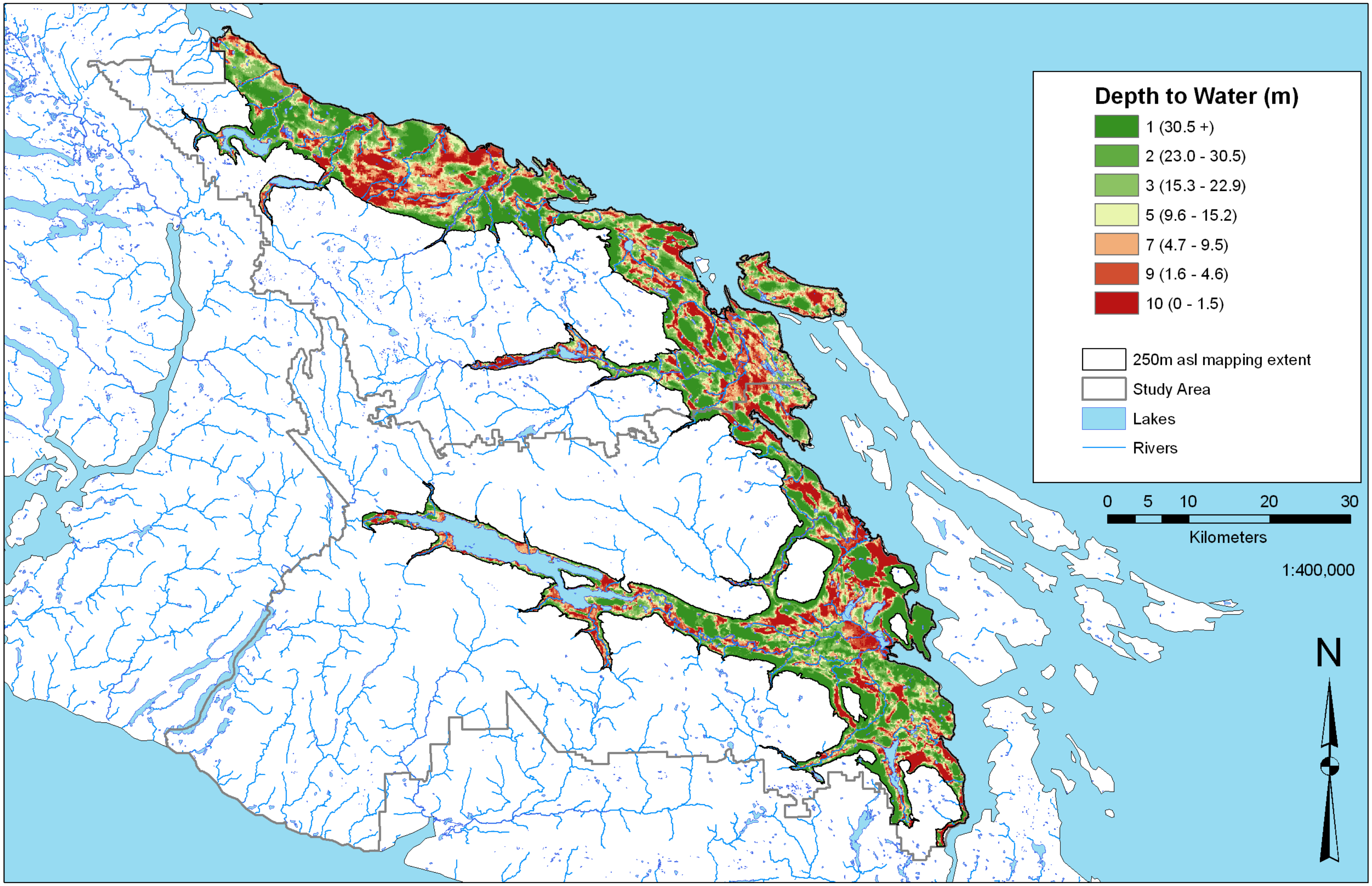
Depth to Water Interpolation

Of the 11 664 wells in the study area, 5 478 were used to interpolate the depth to water parameter. The depth to water in unconfined wells, or top of aquifer in confined wells, was converted into an elevation using the digital elevation model (DEM, i.e. ground elevation minus water depth). Control points were added along rivers and lake shores by converting the line features to points, and assigning a water elevation equal to the ground elevation of the DEM (i.e. depth to water of zero). Zero-elevation control points were added manually along the coast to ensure the entire area of interest was covered by the interpolation. The elevation values from wells and control points were interpolated using the natural neighbour method on a 100 m grid. Once the water elevation was gridded, the depth to water was determined by subtracting the water elevation grid from the DEM. Some areas were interpolated to have a water elevation that was higher than ground elevation (i.e. depth to water was above ground) because the water elevation was interpolated independently of the ground surface. Upon the subtraction of ground elevation and water elevation, some areas of depressions appeared to have water levels above ground since there were no well data in these areas to ‘push’ the water elevation below ground. All areas interpolated to be above ground surface were rated 10, as it is likely that the depth to water is low in these areas. More well information in these areas would allow for refinement of the depth to water dataset. The rating table used to assign vulnerability ratings to the depth to water followed the original US Environmental Protection Agency (EPA) table (Table 5.1, Figure 5.6).

Table 5.1 Depth to water rating table

Depth to water range (ft)	Depth to water range (m)	Rating
100+	30.5+	1
75 – 100	23.0 – 30.5	2
50 – 75	15.3 – 22.9	3
30 – 50	9.6 – 15.2	5
15 – 30	4.7 – 9.5	7
5 – 15	1.6 – 4.6	9
0 – 5	0 – 1.5	10

Figure 5.6 Depth to water parameter, rated according to Table 5.1



5.3. Recharge

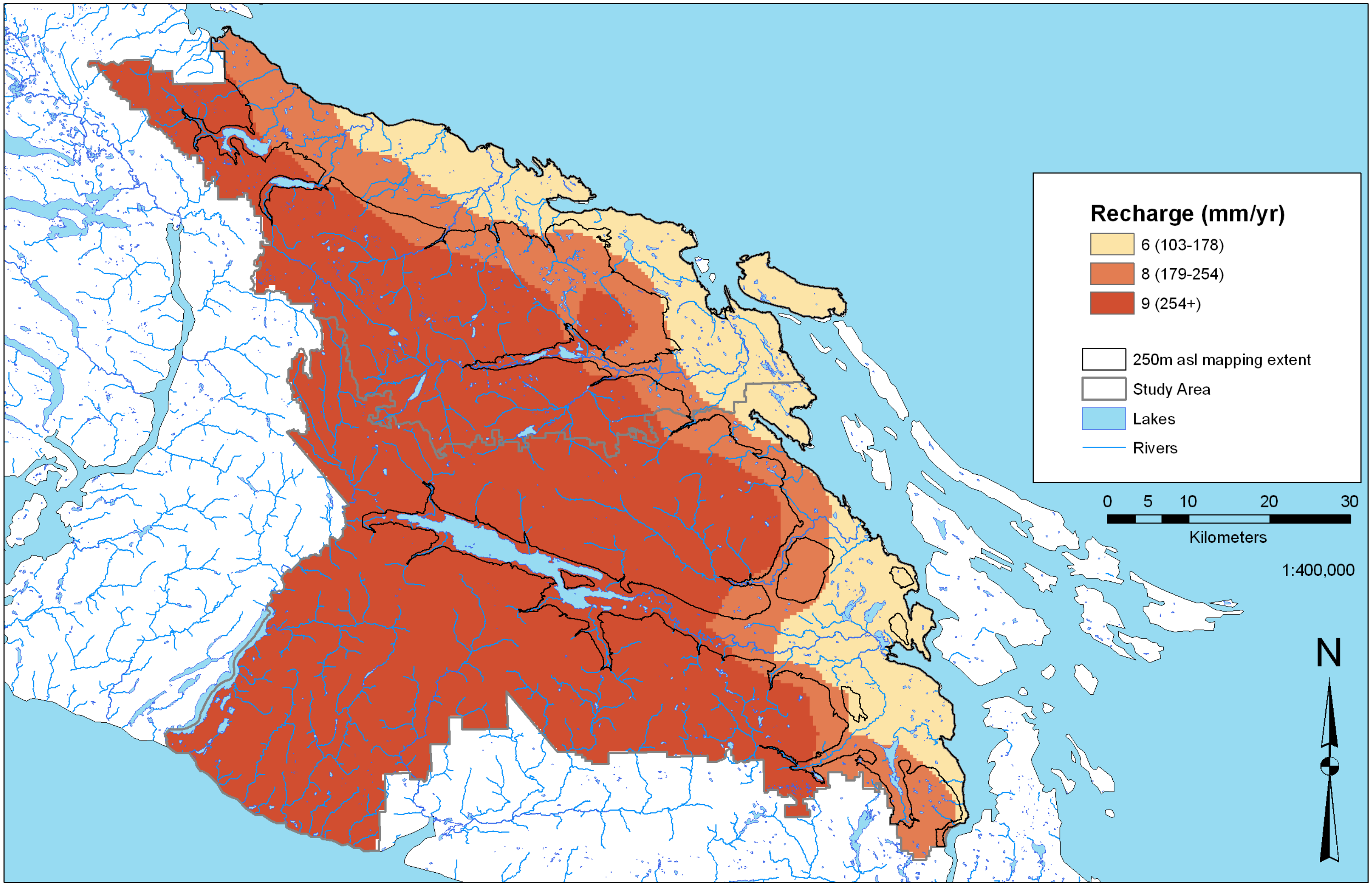
Recharge is an important process that can drive contaminants into the subsurface and towards the water table. Recharge is weighted highly in the DRASTIC calculation; however, recharge is spatially variable and uncertain, creating challenges for mapping this parameter over a regional scale (e.g. Liggett 2008, Scanlon et al. 2002, Hendrickx and Walker 1997). In the study area, recharge was estimated in the study area from gridded precipitation data based on a percent of precipitation. Gridded (400m) precipitation data was available for Vancouver Island from ClimateBC, which is downscaled from PRISM data for the 1961-1990 period (Spittlehouse 2006).

A monthly water balance was calculated for several important watersheds in the study area including the Chemainus River, Nanaimo River and Englishman River based on Climate BC and Environment Canada weather station data (to derive precipitation and estimate evapotranspiration based on Thornthwaite's method, see Thornthwaite 1948) and surface runoff from stream discharge data from Environment Canada stream gauge data. From the water balance, an annual surplus of between 5% and 16% of the annual precipitation cannot be accounted for, but likely exits each watershed as groundwater within the floodplain, or is accounted for by errors in the estimation method. The maximum amount of water entering all forms of temporary storage (i.e. snow, soil, and groundwater) is between 20% and 26% of annual precipitation as suggested by the calculated variation in storage. As the amount of recharge lies between about 5% and 25% of average annual precipitation, groundwater recharge is estimated as 15% of annual precipitation to be conservative. Recharge was rated according to the original US EPA rating table (Table 5.2). Almost all of the study area is rated an 8 or 9 (Figure 5.7).

Table 5.2 Net recharge ranges and ratings

Net Recharge (in/yr)	**Net Recharge (mm/yr)**	**Rating**
0 – 2	0 – 51	1
2 – 4	52 – 102	3
4 – 7	103 – 178	6
7 – 10	179 – 254	8
10 +	254 +	9

Figure 5.7 Recharge parameter, rated according to Table 5.2



5.4. Aquifer Medium

In general, larger grain sizes and more intense fracturing of an aquifer lead to a higher vulnerability, because of decreased capacity for natural attenuation in more permeable aquifers (Aller et al. 1987). The DRASTIC map of the study area represents the intrinsic vulnerability of the uppermost aquifer to contamination (e.g. does not consider the vulnerability of lower aquifers in layered systems, or perched water tables). The aquifer medium was determined for each of the six types of aquifers in the study area (Section 5.1, Figure 5.3).

The aquifer medium for all mapped surficial aquifers (types A, B, and C) was determined and rated based on the material(s) recorded in the aquifer worksheets. In areas of unmapped surficial aquifers (type E), the aquifer medium parameter was based on the uppermost texture identified by the terrain map. Finally, in both mapped and unmapped bedrock aquifers (types D and F) the material and rating was assigned based on the bedrock geology map. For the mapped bedrock aquifers, this approach was taken to maintain rock type boundaries instead of generalizing the material over the whole aquifer polygon.

The terrain map and bedrock geology map are used in mapping both the *A* and *I* parameters. Since the material types are the same, the rating tables for the *A* and *I* parameter were combined into a single table for use with both parameters (Table 5.3). Although the ratings for each material type are the same as for both *A* and *I*, the maps are different because the aquifer medium is not always the same material as the vadose zone medium.

Ratings are assigned to each material or rock as typical ratings based on commonly found properties. The ratings are similar to the typical ratings suggested in the original DRASTIC study (Aller et al. 1987), although these may be adjusted if more detailed information (e.g. local and/or field studies) becomes available. Previous work completed on the Gulf Islands (Mackie 2002, Surrette et al. 2008) showed that the interbedded mudstone and sandstone formations of the Nanaimo Group rocks are more permeable than the sandstone dominated formations due to their increased degree of fracturing. While it is apparent from the large scale lineament map that there is a difference in the fracture density of other units on Vancouver Island, there is little data to support a linkage between fracture intensity and permeability at this regional scale. The ratings in Table 5.3 include all bedrock formations on Vancouver Island. Figure 5.8 shows the aquifer medium ratings for the study area.

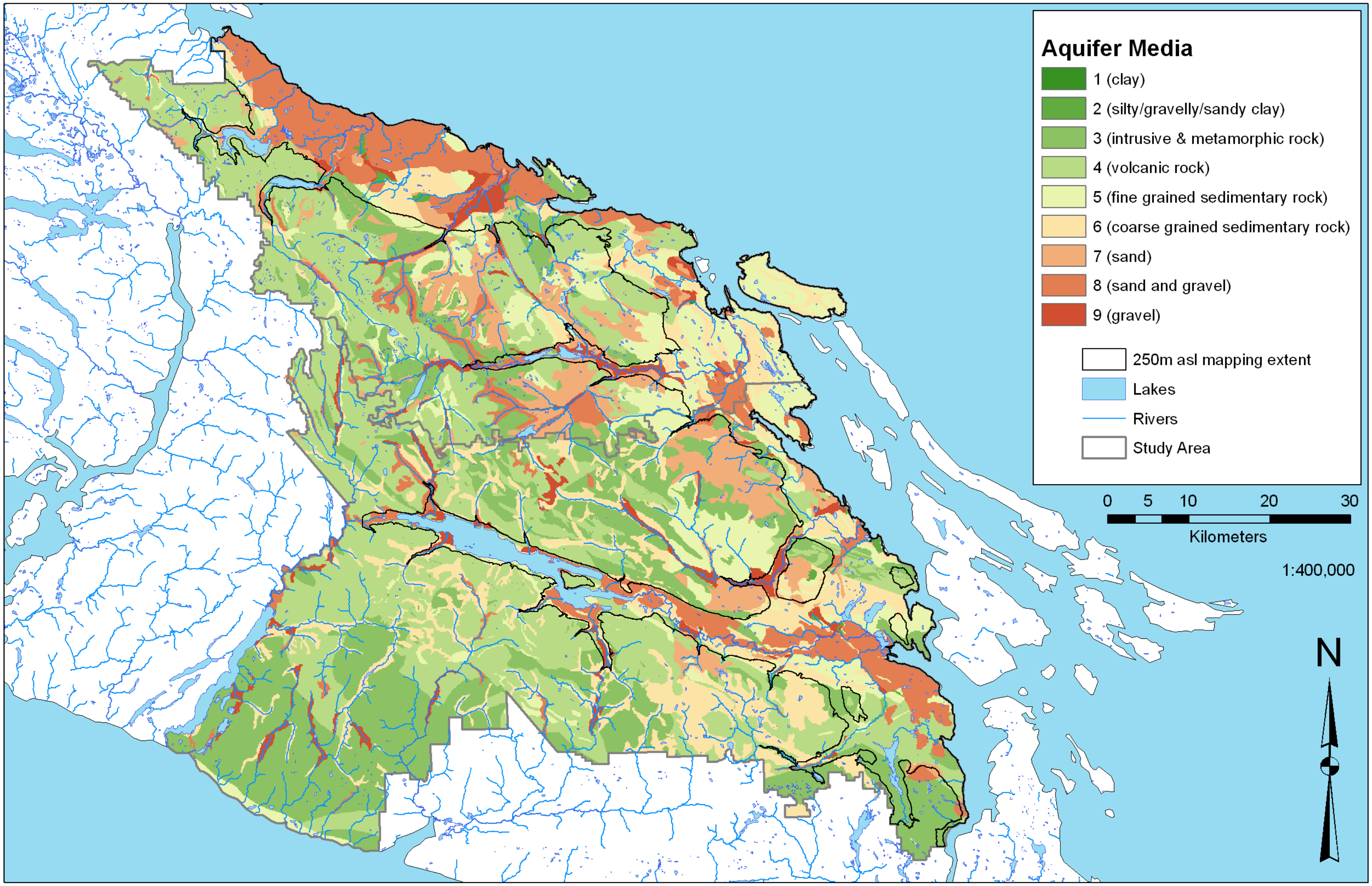
Table 5.3 Aquifer medium and impact of the vadose zone rating table

Bedrock Formation (Fm = Formation; Grp = Group)	Bedrock Material	Mapped Surficial Aquifer Material	Terrain Map Material	*A* and *I* Rating
		confining layer	Clay	1
			Silty clay, gravelly silty clay, sandy clay	2
• West Coast Crystalline Complex (Wark Gneiss, Mount Hall Gabbro, Colquitz Gneiss, undivided West Coast Complex) • Saltspring Intrusive Suite • Buttle Lake Grp (4th Lake Fm, 4th Lake Volcanics) • Island Plutonic Suite • Pacific Rim Complex (Leech River metasedimentary) • Unnamed Cretaceous intrusions • Clayoquot Plutonic Suite • Catface Intrusions • Mount Washington Plutonic Suite • Metchosin Igneous Complex (Sooke Gabbro, Sheeted Dykes)	Mainly crystalline igneous and metamorphic rock, some siliciclastics. - amphibolite, metadiorite, metagabbro, paragneiss, granodiorite, porphyry, diabase, gabbro, diorite, schist, slate, metagreywacke, intrusive rocks (undivided), chert, siliceous argillite, siliciclastic rocks, basalt flows (Massive)		Clayey silt	3
• Sicker Grp (Duck Lake Fm, Nitinat Fm, McLaughlin Ridge Fm, undivided Sicker Grp) • Vancouver Grp (Karmutsen Fm) • Bonanza Grp (Bonanza Volcanics) • Pacific Rim Complex (Leech River metavolcanic, undivided Pacific Rim Complex) • Gambier Grp (Gambier Fm) • Flores Volcanics • Alert Bay Volcanics • Metchosin Igneous Complex (Mechosin Volcanics, Mechosin Fm)	Mainly volcanic rock, some sedimentary and metasedimentary - basaltic flows (pillowed), breccia, tuff, undivided volcanics, volcanicalstic wacke, schist, metarhyolite, volcaniclastic sandstone, metabasalt, andesite-rhyolite, siltstone, argillite			4

Table 5.3 (con't) Aquifer medium and impact of the vadose zone rating table

Bedrock Formation (Fm = Formation; Grp = Group)	Bedrock Material	Mapped Surficial Aquifer Material	Terrain Map Material	*A* and *I* Rating
• Buttle Lake Grp (Mount Mark Fm) • Vancouver Group (Daonella Beds, Quatsino Fm, Parson Bay Fm, undivided Vancouver Grp) • Bonanza Grp (Harbledown Fm) • Kyuquot Grp • Nanaimo Grp (Sidney Island Fm, Comox Fm, Extension Fm, Protection Fm, De Courcy Fm, Geoffrey Fm, Gabriola Fm) *	Limestone, fine grained sedimentary rock (non-Nanaimo Grp), coarse grained sedimentary rock (Nanaimo Grp) - limestone bioherm/reef, mudstone, siltstone, shale, limestone, slate, argillite, marine sedimentary and volcanics, undivided sedimentary, sandstone, conglomerate, arenite		Silt, bouldery silt, sandy silt	5
• Buttle Lake Group (Nanoose Complex, St. Mary's Lake Fm, undivided Buttle Lake Grp) • Mixed Buttle Lake Grp and Mount Hall Gabbro • Queen Charlotte Grp • Nanaimo Grp (Haslam Fm, Pender Fm, Cedar District Fm, Northumberland Fm, Spray Fm, Suquash Sequence, undivided Nanaimo Grp) * • Chuckanut Fm • Carmanah Grp	Coarse grained sedimentary (Non-Nanaimo Grp) and fine grained sedimentary (Nanaimo Grp) - undivided sedimentary, coarse clastic sedimentary, argillite, limestone, sandstone, conglomerate, greywacke, siltstone, mudstone, arenite, shale		Alluvium, organics, undifferentiated, silty sand	6
		Sand	Sand	7
		Sand and gravel,	Colluvium, fluvial, bouldery sand, gravelly sand, rubbley sand, sandy boulders, sandy gravel	8
* Note, all of the Nanaimo Group, and Sicker Group are rated one value higher than in the Gulf Islands (Denny et al. 2007) to fit into ratings once other rocks and materials were considered.		Gravel	Mixed fragments, gravel, gravely boulders, gravelly mixed fragments, rubble	9
				10

Figure 5.8 Aquifer medium parameter, rated according to Table 5.3



5.5. Soil Medium

The thickness and texture of the soil can influence the natural attenuation capacity and permeability of the soil zone. Unfractured clays and silts will provide a barrier to flow and have a lower vulnerability than more permeable sands (Aller et al. 1987).

A number of soil surveys have been completed for Vancouver Island. Two soil surveys, with texture and drainage information, are available from the National Soils Database, one at a scale of 1:100 000 for southern Vancouver Island (Jungen 1985), and one at 1:20 000 for Gabriola Island (Kenney et al. 1989). A series of 1:20 000 maps (CAPAMP project, BC MoE), with detailed soil attributes, are available at scales of 1:20 000 but do not cover all areas below the 250m contour line. Therefore, the 1:100 000 map of southern Vancouver Island (Jungen 1985) and 1:20 000 map of Gabriola Island (Kenney et al. 1989) were used to map the soil medium to ensure coverage over the entire study area and the rest of southern Vancouver Island. When the intrinsic vulnerability is mapped in other areas of Vancouver Island, alternate sources of soils information, such as the terrain map, may have to be used as the 1:100 000 map is only available in digital format for the southern half of Vancouver Island.

Soils from the maps by Jungen (1985) and Kenney et al. (1989) were rated based on the soil drainage (Table 5.4) from the dominant soil type in each polygon (Table 5.5), providing coverage over the entire study area (Figure 5.9). Using soil drainage to determine vulnerability of the soil differs from the original DRASTIC method where the soil texture is used to rate vulnerability. Soil drainage is an observed property of the soil type, based on the ability of the soil to transmit water as a whole (Luttmerding et al. 1990). Therefore, permeable pathways in the soil, such as macropores or fissures, can be accounted for in the vulnerability parameter by using soil drainage, rather than on texture alone.

Table 5.4 Soil drainage types and ratings

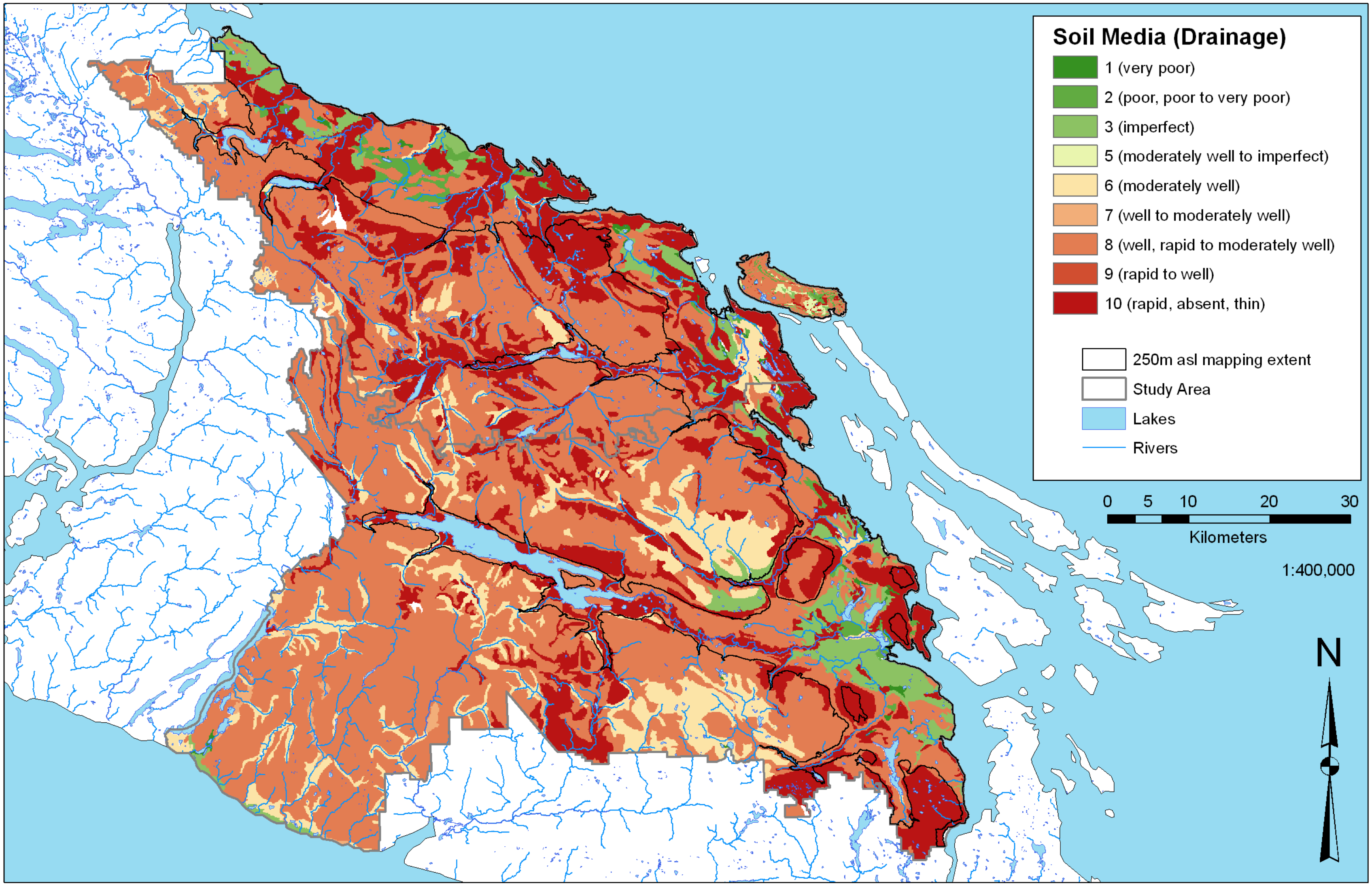
Soil Drainage	Rating
Very poor	1
Poor, poor to very poor	2
Imperfect	3
Moderately well to imperfect	5
Moderately well	6
Well to moderately well	7
Well, rapid to moderately well	8
Rapid to well	9
Rapid, absent/thin	10

Table 5.5 Soil associations of the Regional District of Nanaimo and Cowichan Valley Regional District with dominant drainage and soil medium rating.

Note: Numbers in brackets are soil association components. Soil associations in italics are from Gabriola soil survey (Kenney et al. 1989).

Soil Association	Drainage	*S* Rating
Aveline (1,2), Arrowsmith (1,3,7), Ampitrite (2), Azilion (1,2,3,9), *Metchosin*	Very poor	1
Cowichan, Denman Island	Poor to very poor	2
Cowichan (1,4), Crofthill (1,4,9), Tolmie (1,4), Tagner (4,7*), Parksville, Suffolk (pd), Tolmie*	Poor	2
Bowser (1,2,4), Chemainus (7), Chemainus River (7,9), Fairbridge (1), Finlayson (1,2), Genoa Bay (9), Kootowls (7), Royston (1,3,4), Brigantine, Baynes, Chemainus (-,id), Fairbridge, Mexicana (id), Suffolk, Tricomal (id)	Imperfect	3
Mexicana, Suffolk, Tricoma	Moderately well to imperfect	5
Chemainus (1,4), Chemainus River (4), Fleetwood (1,3,4), Goldstream (1,2), Green Mountain (1), Grierson (1), Hepatzl (-,2), Kennedy Lake (1,5), Moyeha (1,3,4), Quibble (1,2,5), Ronald (1,2,5,7), Rowland (1,3), Reegan (1,2,3,4,7), Rosander (2), Snuggery (4), Shofield (1,2,3,5), Sarita (1,3,4)	Moderately well	6
Holford (3,4,7), Hooper (1,4)	Well to moderately well	7
Beddis	Rapid to moderately well	8
Beavertail (1), Cadboro (3), Cottam (1), Crespi (1,2), Council (1), Cotter (1), Cullite (1,3), Chetwood (3), Dashwood (1,2,4), Dashwood Creek (1,3), Guemes (1,2), Granita (1,5), Haslam (1,5), Healey (1), Hankin (1,7), Hooper (8), Hatzite (1,3,4,6), Holyoak (1,2,5,6), Kildonan (1,3), Langford (3), Lemmens (6), Nitnat (1,3,4,5,6), Quinsam (1,2,4,5,7), Quimper (1,2,3,4,5), Quatsino (1,3), Robertson (1,2,5), Reginald (3,5,6,7), Ritherton (1,2,3,5,6,7), Rainer (1,2,5,6,7), Reeses (1,2,5,6,7), Rossiter (1,2,3,4,5), Rutley (1,3,5,6), Shawnigan (1,2,3,5), Shelbert (1,3,5), Stockett (3), Somenos (1,2,5), Smokehouse (3,5,6), Shirmish (1,2,5,6,7), Sprise (1,2,5,6,7), Snakehead (3,5,6), *Galiano, Neptune, Saturna*	Well	8
Bellhouse, Qualicum	Rapid to well	9
Cassidy (1,4), Errington (1), Genoa Bay (4), Hawarth (-,1,2,7,8), Huffer (5), Hemmingsen (5,6), Hiller (1,3,5,6), Honeymoon (1,2,3,4,5,7,8), Hesqualt (6), Kuhushan (4), Kye (1,2), Nootka (7), Plggott (1,2,5), Qualicum (1,2,3,4,5,8), Quamichan (1,3,4,5), Robertson (6), Ragbark (5,6), Rosewall (1,3,5,6), Rossiter (6), Sprucebark (1,5,8), Squaily (1,3,5), Shepherd (1,2,5,6), Strata (1,3,4,5,6), Tzuhalem (1,2,5,6),	Rapid	10
Rock outcrop, made land (soil absent)	None	10
Coastal beach, Water, Tidal flats	None	None

Figure 5.9 Soil medium parameter, rated according to Table 5.4



5.6. Topography

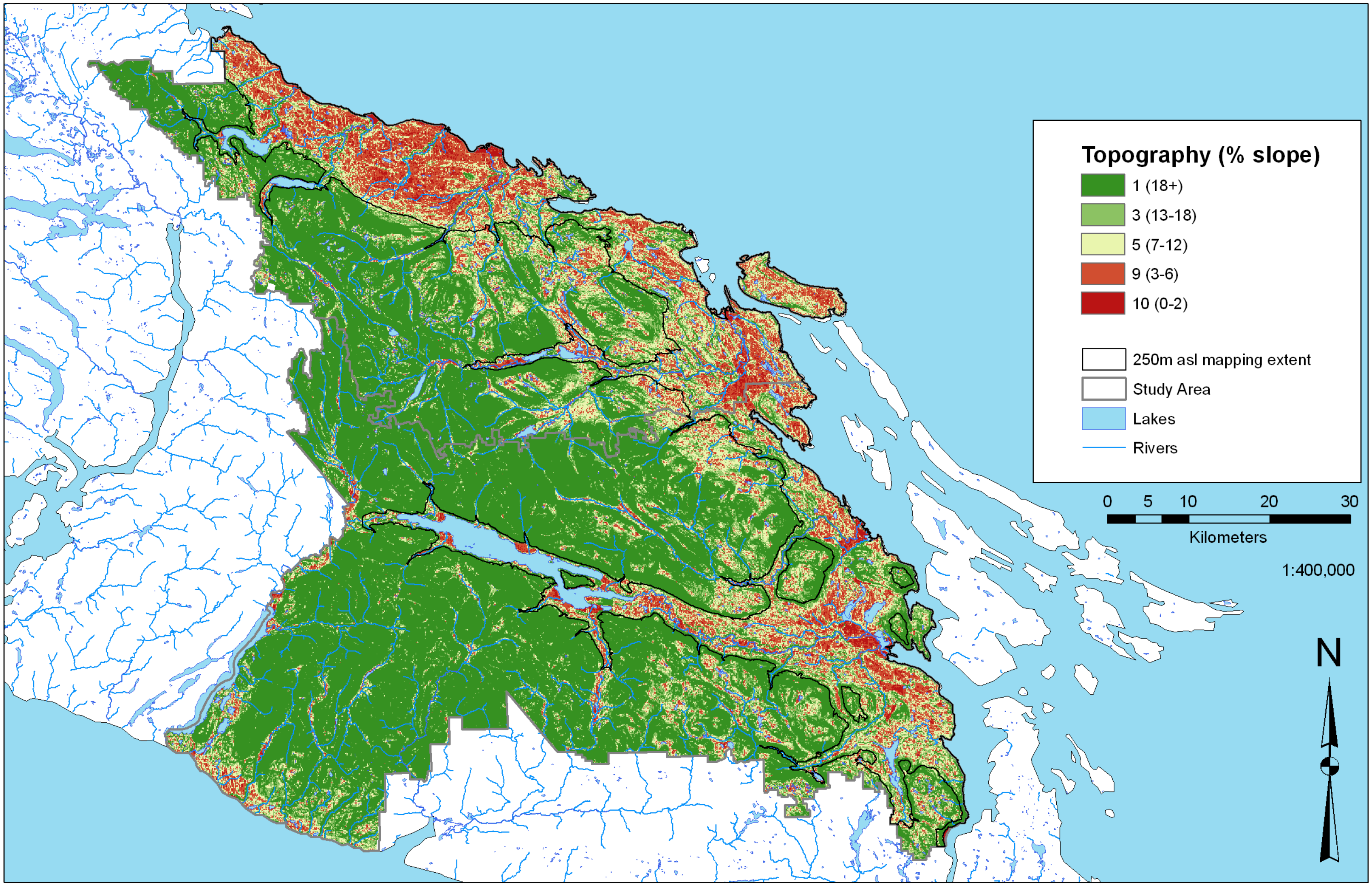
The vulnerability due to topography is assessed by the slope of the land surface. The greater the slope, the more potential for runoff, and less potential for infiltration of contaminants; therefore, the vulnerability is lower (Aller et al. 1987).

Topography is a very straightforward parameter to determine, especially with the widespread availability of DEM's and the analytical capability of GIS software. Slope was calculated from the DEM and rated according to the original US EPA rating tables (Table 5.6, Figure 5.10).

Table 5.6 Topography (slope) ranges and ratings

Topography (Slope %)	Rating
18+	1
13 – 18	3
7 – 12	5
3 – 6	9
0 – 2	10

Figure 5.10 Topography parameter, rated according to Table 5.6



5.7. Impact of the Vadose Zone

Similar to soil medium, the vadose zone is rated based on the materials' natural attenuation capacity and permeability. The more permeable a material, the shorter the transit time and lower the attenuation capacity; hence, the more vulnerable (Aller et al. 1987).

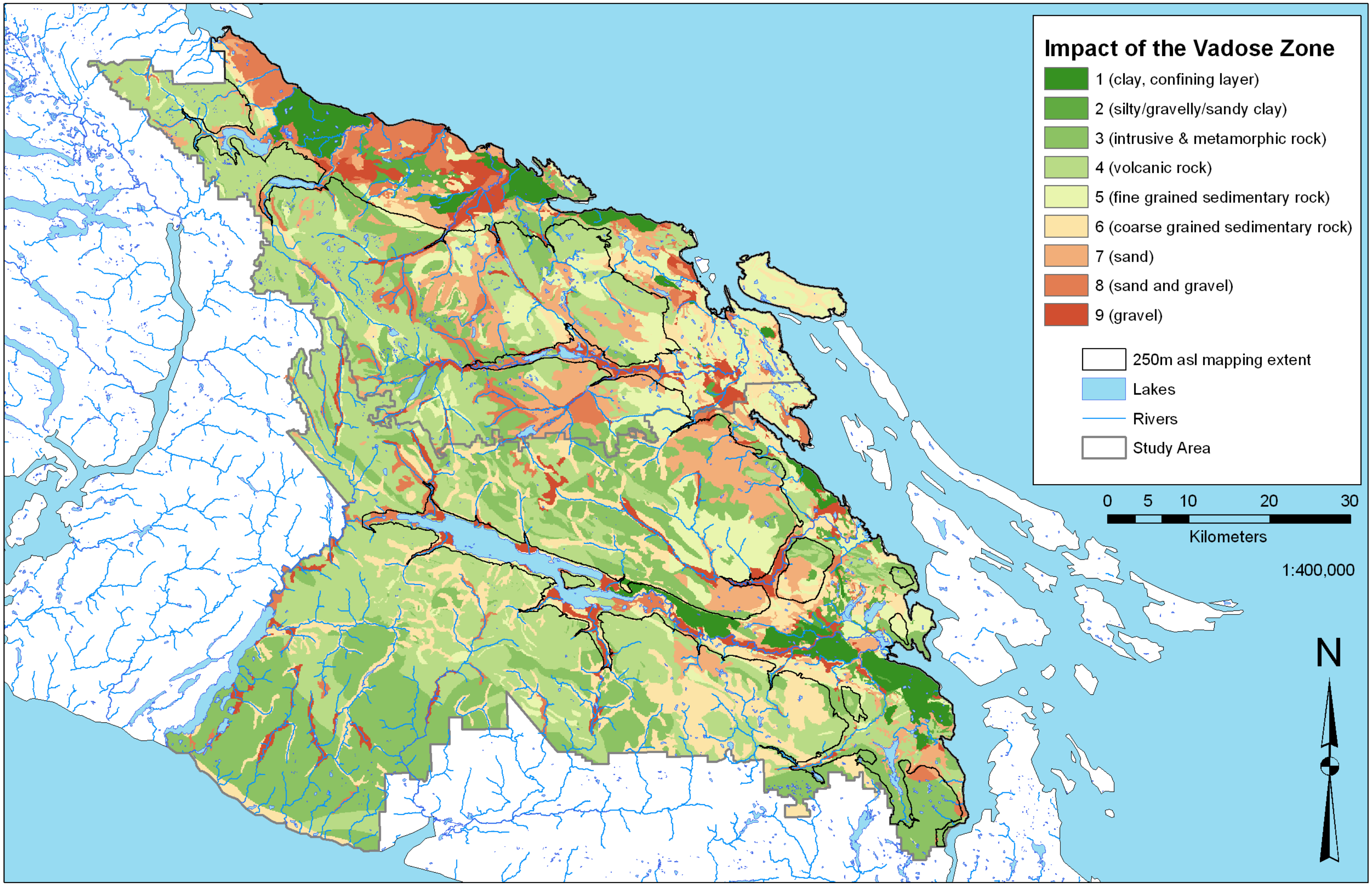
Like the depth to water and aquifer medium parameters, the method used to identify the vadose zone material depended on the type of aquifer. For mapped confined aquifers, the vadose zone is assigned the lowest vulnerability rating of 1, following the original method by Aller et al. (1987). For mapped unconfined and partially confined surficial aquifers, the vadose zone material was identified from the uppermost texture in the terrain map. The terrain map was also used to identify the vadose zone material in unmapped surficial aquifers.

For bedrock aquifers within the 250 m asl area of interest, where the depth to water map was interpolated (i.e. where there are well data), the vadose zone was identified based on the relationship between depth to water, depth to bedrock, and overburden thickness. In areas where the majority of the vadose zone was surficial material, the terrain map was used to rate the vadose zone parameter. Conversely, in areas where the majority of the vadose zone was bedrock material, then the bedrock geology map was used to rate the vadose zone. For example, if an area had an interpolated depth to water table of 20m, and the overburden map showed a thickness of 15m, then the vadose zone was interpreted to consist of surficial sediments and was rated according to the uppermost texture from the terrain map.

Finally, for bedrock aquifers where there were no well data to determine the overburden thickness, the bedrock material was used to represent the vadose zone material since these areas were already determined to have little overburden, according to the terrain map.

The vadose zone media were rated according to Table 5.3. Although the ratings for each material type are the same as for aquifer medium, the maps are different because the aquifer medium is not always the same material as the vadose zone medium. The map of the impact of the vadose zone is shown in Figure 5.11.

Figure 5.11 Impact of the vadose zone parameter, rated according to Table 5.3



5.8. Conductivity

The faster that water and contaminants can move through an aquifer, the greater the likelihood of the contaminant spreading from its source. Subsequently, the higher the hydraulic conductivity of an aquifer, the higher the vulnerability (Aller et al. 1987).

Hydraulic conductivity is typically determined in the field using pumping tests. Although only one of the reports from the hydrogeological report compilation (Section 4.2) included hydraulic conductivity, many contained transmissivity (T) measurements and others only contained specific capacity (SC) measurements. Hydraulic conductivity was determined by dividing T by the effective aquifer thickness. For wells without a reported T value, the T was calculated by determining a linear relationship between SC and T, following the method by Razack and Huntley (1991).

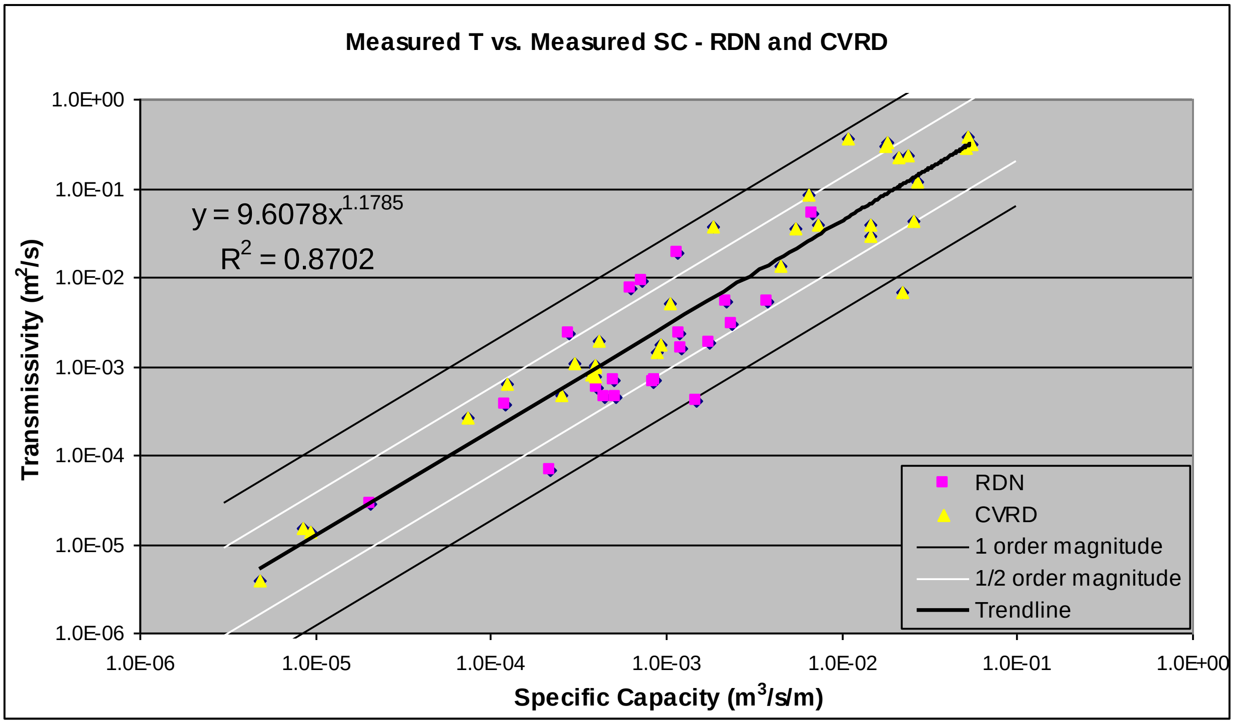
From the compiled hydrogeological reports, data on 38 wells in the RDN were collected, with T and SC values reported for 21 wells (55%), T only reported for 4 wells (11%), and SC only reported for 13 wells (34%). In the CVRD there was information on 54 wells: T and SC values were reported for 32 wells (59%), T only reported for 14 wells (26%), and SC only for 8 wells (15%). Combining the RDN and CVRD, there are 53 pairs of T and SC values with which to develop a relationship for calculating T for the 21 wells with only SC recorded (Figure 5.12). Some wells had either multiple pumping tests, multiple methods of analysis for T (e.g. Cooper-Jacob or Theis), or multiple T's calculated from numerous wells (e.g. pumping well and two observation wells). In these cases the geometric mean of all T's given was calculated.

The relationship between SC and T for the study area is given in Equation 5.1:

$$T = 9.6078\ SC^{1.1785} \qquad (5.1)$$

The correlation between T and SC is very high (R^2=0.87). Overall, 39 wells (74% of the wells) were within half an order of magnitude of the predicted T, and 51 wells (96% of the wells) were within an order of magnitude (Figure 5.12). Equation 5.1 was applied to wells for which only a SC was reported to determine T.

Figure 5.12 Relationship between transmissivity and specific capacity for measurements in wells in the Regional District of Nanaimo and Cowichan Valley Regional District.



The reported T values (71 wells), and calculated T values (21 wells), were used to determine hydraulic conductivity by dividing T by an estimated effective aquifer thickness. Since a well rarely fully penetrates the aquifer, the screen length was used as the estimated effective aquifer thickness for surficial wells. Selecting the screen length as the aquifer thickness will generally result in higher hydraulic conductivity values, as the screen length can be much smaller than the actual aquifer thickness. For bedrock wells, the effective aquifer thickness was determined by taking 5% of the open hole interval (length between the bottom of the surface casing and the bottom of the hole) (Carmichael et al. 2008). This assumes that in most bedrock aquifers the majority of water flow is moving through the fractures in a relatively impermeable aquifer material. Hydraulic conductivity was calculated for 64 wells in 20 aquifers in the study area (Table 5.7). The screen length was not available for 23 wells, and 5 wells were drilled in unidentified aquifers. The hydraulic conductivities calculated from the T and screen length are higher than what would be expected for the study area, however these values are used to provide a conservative (high) estimate of the vulnerability of the aquifers. Even though the absolute values of the conductivities may be high, the relative relationship between different aquifers is maintained.

Table 5.7 Geometric mean of transmissivity and hydraulic conductivity for aquifers in the study area.

Note: The C rating is based on the original table in Aller et al. (1987), as shown in Table 5.9. Some of the aquifers below are not the uppermost aquifer but were completed in the same formation as the uppermost aquifers.

Aquifer	Aquifer Type	Formation (from aquifer worksheets)	T (m^2/s)	K (m/s)	K (m/d)	Number of wells	C Rating
202	Bedrock	Bonanza Grp and Sicker Volcanics	4.25E-05	1.60E-05	1.71E-01	2	1
204	Bedrock	Island Intrusions	1.42E-05	1.98E-06	1.39E+00	2	1
218	Bedrock	Benson Fm (Nanaimo Grp)	6.03E-05	2.14E-05	1.85E+00	1	1
215	Confined	Quadra Sand	1.31E-03	3.27E-04	2.82E+01	4	4
216	Partially Confined	Quadra Sand	1.41E-03	4.09E-04	3.53E+01	3	4
217	Partially Confined	Quadra Sand	9.87E-04	3.85E-04	3.33E+01	12	4
219	Confined	Quadra Sand	7.78E-04	2.77E-04	2.39E+01	8	4
205	Confined	Vashon Drift	3.11E-03	1.15E-03	9.96E+01	1	8
161	Unconfined	Capilano Sediments	3.32E-01	6.91E-02	5.97E+03	1	10
163	Confined	Quadra Sand	5.28E-02	3.52E-02	3.04E+03	1	10
172	Unconfined	Salish Sediments	1.51E-01	4.80E-02	4.14E+03	8	10
186	Unconfined	Salish Sediments	1.20E-01	2.20E-02	1.90E+03	6	10
187/188	Confined	Salish Sediments	4.19E-02	1.48E-02	1.28E+03	7	10
188	Confined	Vashon Drift	5.29E-02	2.27E-02	1.96E+03	2	10
189	Unconfined	Salish Sediments	1.34E-02	4.48E-03	3.87E+02	1	10
190	Unconfined	Salish Sediments	6.17E-03	2.52E-03	2.18E+02	4	10
197	Confined	Vashon Drift	1.12E-03	1.44E-03	1.25E+02	3	10
221	Unconfined	Salish Sediments	1.26E-02	3.16E-03	2.73E+02	1	10
416	Unconfined	Quadra Sand	1.87E-02	3.06E-03	2.65E+02	1	10
207	Bedrock	Bonanza group and island intrusions	7.75E-05	1.57E-02	1.36E+03	1	10

The hydrogeologic report compilation produced conductivity values for some of the mapped aquifers in the study area, but many, including the unmapped aquifers, do not have estimates of hydraulic conductivity. Mapped surficial aquifers were rated based on the geometric average hydraulic conductivity from all wells completed in the same geologic formation (Table 5.8), and using the original rating table shown in Aller et al. (1987) (Table 5.9). All mapped surficial aquifers consisting of Capilano Sediments, Vashon Drift, and Salish Sediments were assigned a rating of 10, while mapped aquifers consisting of

Quadra Sand material were rated 6 (Table 5.8). It is noted that hydraulic conductivity information was completed from one well in the Capilano Sediments, therefore the rating for aquifers consisting of these sediments may change as more hydraulic conductivity information becomes available.

A few mapped surficial aquifers had no geologic formation information but were composed of sand and gravel. These aquifers were also rated 10, following with the majority of other surficial aquifers in the study area. All bedrock aquifers were rated 1 (Table 5.8). The remaining aquifers consist of unmapped surficial aquifers, where the terrain map was used to define the aquifer material. For these aquifers, the conductivity was rated based on textbook values for those particular sediment types (Table 5.9). The rated hydraulic conductivity map for the study area is shown in Figure 5.13.

Although fine grained sediments in the Vashon Drift and Capilano Sediments are barriers to groundwater flow and form most of the confining layers in the study area, they also include deposits of outwash and deltaic sands and gravels which host productive aquifers (Fyles 1963). It was unexpected that wells in the Quadra Sediments had distinctly lower conductivities than wells in the Vashon Drift and Capilano Sediments. Re-analysis of the pumping test from the hydrogeological reports with consistent methods, or the inclusion of more wells in the analysis of the Capilano Sediments and Vashon Drift, may yield different results.

Table 5.8. Geometric mean of hydraulic conductivity and rating for mapped aquifer formations

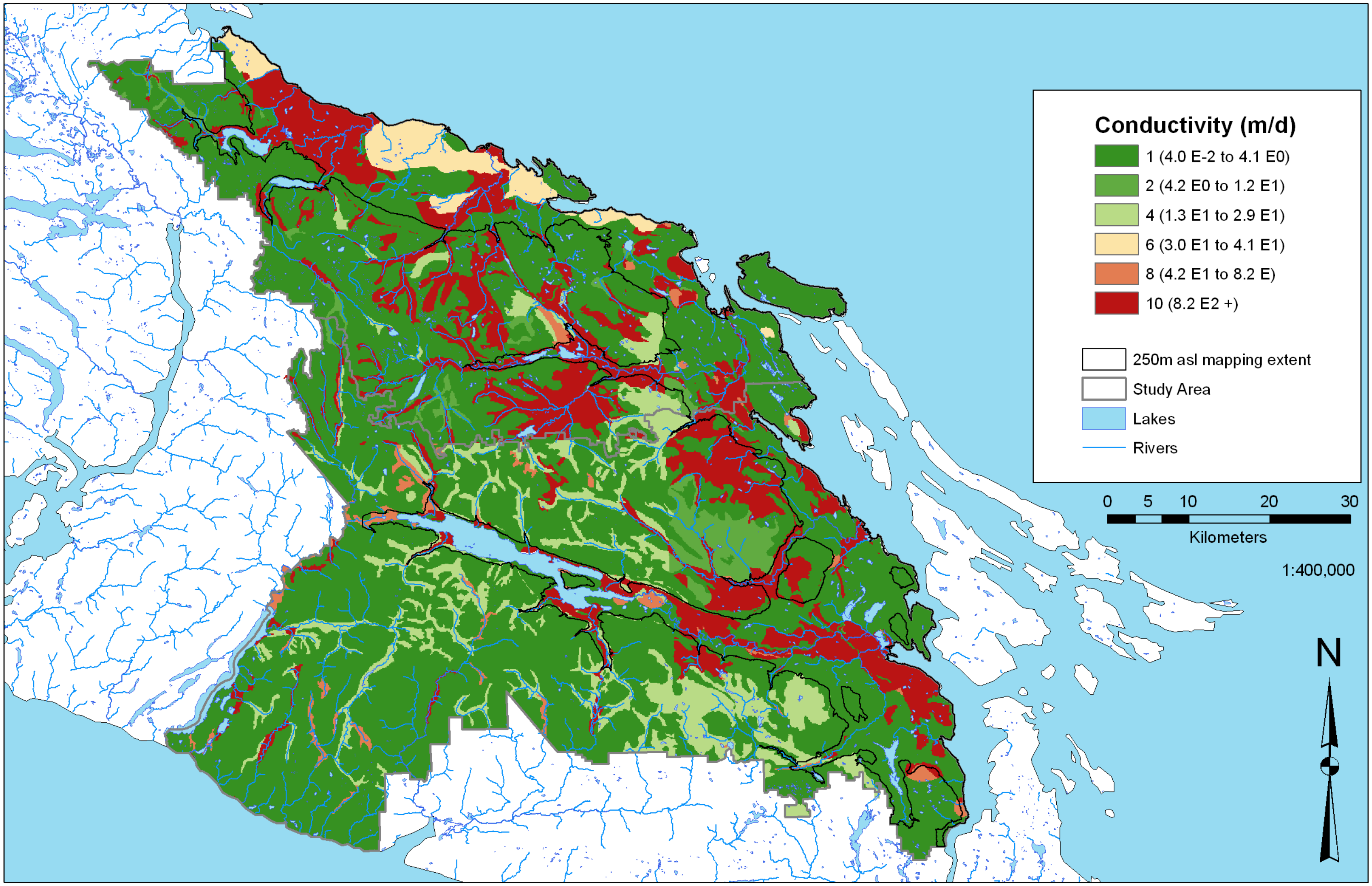
Formation (from aquifer worksheets)	**T (m^2/s)**	**K (m/s)**	**K (m/d)**	**Number of wells**	**C Rating**
Bedrock	4.10E-05	9.54E-06	6.35E-01	6	1
Quadra	1.22E-03	4.34E-04	3.75E+01	29	6
Vashon	2.36E-03	3.48E-03	3.01E+02	6	10
Salish	4.92E-02	1.59E-02	1.37E+03	27	10
Capilano	3.32E-01	6.91E-02	5.97E+03	1	10

Table 5.9 Hydraulic conductivity rating table for all materials in the study area.

(B) = aquifer material from bedrock map (mapped and unmapped bedrock aquifers); (W) = aquifer material from aquifer worksheets (mapped surficial aquifers); (T) = aquifer material from terrain map (unmapped surficial aquifers)

K (m/d)	**Formation/lithology**	***C*** **Rating**
$4.0\text{x}10^{-2} – 4.1\text{x}10^{0}$	Bedrock – all types (B), clay (T), silty clay (T), gravelly silty clay (T), sandy clay (T), clayey silt (T)	1
$4.2\text{x}10^{0} – 1.2\text{x}10^{1}$	Silt (T), sandy silt (T)	2
$1.3\text{x}10^{1} – 2.9\text{x}10^{1}$	morainal (T)	4
$3.0\text{x}10^{1} – 4.1\text{x}10^{1}$	Quadra Sand (W)	6
$4.2\text{x}10^{1} – 8.2\text{x}10^{1}$	Alluvium (T), organics (T), undifferentiated (T), silty sand (T), colluvium (T), fluvial (T), mixed fragments (T)	8
$>8.2\text{x}10^{1}$	Capilano Sediments (W), Vashon Drift (W), Salish Sediments (W), unknown sands and gravels (W), sand (T), bouldery sand (T), gravelly sand (T), rubbly sand (T), sandy boulders (T), sandy gravel (T), mixed fragments (T), gravel (T), gravelly boulders (T), gravelly rubble (T)	10

Figure 5.13 Hydraulic conductivity parameter, rated according to Table 5. 9



5.9. Fractured Media

Denny et al. (2007) introduced a fractured media (*Fm*) parameter into the original DRASTIC methodology to reflect the local hydrogeology of the neighbouring Gulf Islands, which is dominated by bedrock fracture flow (Surrette et al. 2008). The use of the *Fm* parameter in the current study area was evaluated based on correlations between well yields, proximity to fractures, and bedrock type in the study area; however, this evaluation showed that much more detailed work, including fieldwork, would need to be conducted in order to incorporate the *Fm* parameter into the current study.

In the Gulf Islands study three primary fault and fracture characteristics, fracture orientation, fracture length, and fracture intensity, were used to evaluate the *Fm* parameter as part of a larger conceptual framework of how faults and fractures affect intrinsic vulnerability (Denny et al. 2007). The *Fm* analysis was supported by field studies on fault and fracture systems of the area (Journeay and Morrison 1999), field measurement of fracture intensities (Mackie 2002, Surrette and Allen 2008), a well-developed hydrostructural conceptual model (Mackie 2002, Surrette et al. 2008), and groundwater modelling (Surrette and Allen 2008).

The three fracture properties evaluated on the Gulf Islands affected the vulnerability in various ways, as described in Denny et al. (2007). The orientation dictates whether the faults or fractures are likely in a zone of extension or contraction, according to the direction of regional tectonic stress. For the Gulf Islands, high fault/fracture apertures are associated with structures oriented northwest-southeast, in zones of extension, and are likely to form conduits for water or contaminant flow, indicating a high vulnerability. Conversely, low fault/fracture apertures are associated with structures running northeast-southwest, in zones of contraction, and are likely to form barriers to flow, indicating a low vulnerability. Length of the fault/fracture zones influences whether the structure is regional or discreet. Long, regional structures are likely to have more intersections with other structures and, therefore, have a higher vulnerability. Finally, fracture intensity, therefore permeability and vulnerability, increases closer to major faults/fractures (Mackie 2002, Surrette et al. 2008). This increase in vulnerability is represented by a series of buffers around regional structures (Denny et al. 2007).

The use of the *Fm* component for the study area was evaluated. The influence of fractures on groundwater flow on Vancouver Island is known, although it has not been characterized as well as the Gulf Islands. A lineament map, derived from LANDSAT imagery, was available for the southern portion of Vancouver Island. The orientation and length of these lineaments can easily be determined. However, the determination of fracture intensity is much more difficult, as it will depend on rock type and the proximity to regional faults/fractures. While it is possible to use the fracture intensities from matching rock units on the Gulf Islands, there are many more formations on Vancouver Island than the Gulf Islands, and many of the aquifers comprise unconsolidated materials for which fracturing is unlikely to be a significant issue. The fracture density (total fracture length per square kilometre) map, created from the lineament map, can show spatial changes in fracture density and the average fracture density for each formation or rock type (i.e. igneous or sedimentary) can be determined. However, this does not provide an indication of how fracture intensity (number of fractures per meter – determined in the field from scanline mapping) changes in relation to major faults/fractures.

As shown in Caine et al. (1996), fractures can form either conduits or barriers to flow. In an attempt to validate the assumption that greater fracture density (or intensity) leads to increased permeability in Southern Vancouver Island, well yields were compared to both proximity to mapped lineaments, and to average fracture density for particular formations and rock types. No correlation was found between well yield and proximity to fractures, even after the removal of wells with a low locational accuracy (greater than 10m uncertainty), and the separation of fractures in sedimentary formations from those in igneous or metamorphic formations.

The *Fm* component of DRASTIC was not used for the intrinsic vulnerability mapping of the study area. The hydrostratigraphic and hydrostructural conceptual models developed for the Gulf Islands cannot be applied across Vancouver Island without further study supported by field investigations. Even if the conceptual model did apply, there is a lack of fracture intensity data for most of the formations on Vancouver Island. The DRASTIC-Fm approach is a method of including specific fracture information on the hydrogeologic system into the analysis of intrinsic vulnerability. If more specific data on the elements influencing vulnerability of fractures becomes available for the RDN, CVRD, or the rest of Vancouver Island, then the inclusion of the *Fm* parameter could be re-visited.

5.10. DRASTIC Calculation

The DRASTIC calculation used a 100 m grid cell size, although this does not imply that the map is accurate to 100 m. The smallest scale maps used in the analysis were the BCGS bedrock geology map (1:250 000) and the precipitation/recharge map (400m grid cells), and the largest scale maps were the terrain maps (1:50 000) and DEM (25m grid cells).

6.0 RESULTS

Results of the intrinsic vulnerability mapping for the Regional District of Nanaimo and Cowichan Valley Regional District are shown in Figure 6.1. To reiterate, the mapping extent was limited by the availability of well data and the interpolation extent of the depth to water parameter. As more well data become available, the mapping can be extended beyond the current study area using the same methods as outlined in this report. Small holes in the vulnerability map occur in the area below 250 m asl. These are due to small gaps or polygons with no attributes in the original input data. Additionally, along some of the coastal areas, the edge for the vulnerability map does not coincide exactly with the 250 m asl mapping extent polygon, again due to differences in the coastline as mapped in each of the various input data.

In general, the mapped surficial confined aquifers in the study area have moderate to low intrinsic vulnerability, due to the presence of a confining layer and low vadose zone rating, combined with a slightly deeper depth to water. The mapped and unmapped unconfined surficial aquifers have a higher intrinsic vulnerability due to their relatively shallow depth to water, permeable vadose zone and aquifer medium. The bedrock aquifers have a generally low intrinsic vulnerability due to their deep depth to water, and low aquifer medium, conductivity, and vadose zone ratings. The calculated DRASTIC vulnerability of mapped aquifers was more variable, as expected, than the single value assigned using the BC aquifer classification system.

Some parts of the study area have a gradation between high and low vulnerability, while others have a sharp boundary. Sharp boundaries are expected in areas where the geology changes abruptly, whereas gradation boundaries are more common in areas with gradational changes in geology.

The vulnerability map is presented in Figure 6.1 with a continuous colour scale, and ranges from a low vulnerability of 59 to a high values of 218 (23 and 230 are theoretical minimum and maximum). It may be desirable to classify the vulnerability map into set categories for display and usage by stakeholders. As an example, the vulnerability map shown in Figure 6.2 is classified into three categories – high, moderate, and low – for the study area. The breakpoints between these classes were the same as used in Wei (1998). The 1998 study of the Lower Fraser Valley in BC compared results from DRASTIC to another method of mapping vulnerability called Aquifer Vulnerability Index (AVI) and used the comparison to determine the three breakpoints. The original DRASTIC documentation classified the vulnerability scores into eight colour-coded categories; however, no labels were assigned to these categories (e.g. high, low, moderately low, etc.) and the larger number of categories makes interpretation of the map more difficult for planning. Caution should be exercised when classifying the map into specific categories, as this creates a distinct division between two areas even if the actual boundary between them is gradational.

Figure 6.1 Intrinsic aquifer vulnerability map for the Regional District of Nanaimo and Cowichan Valley Regional District

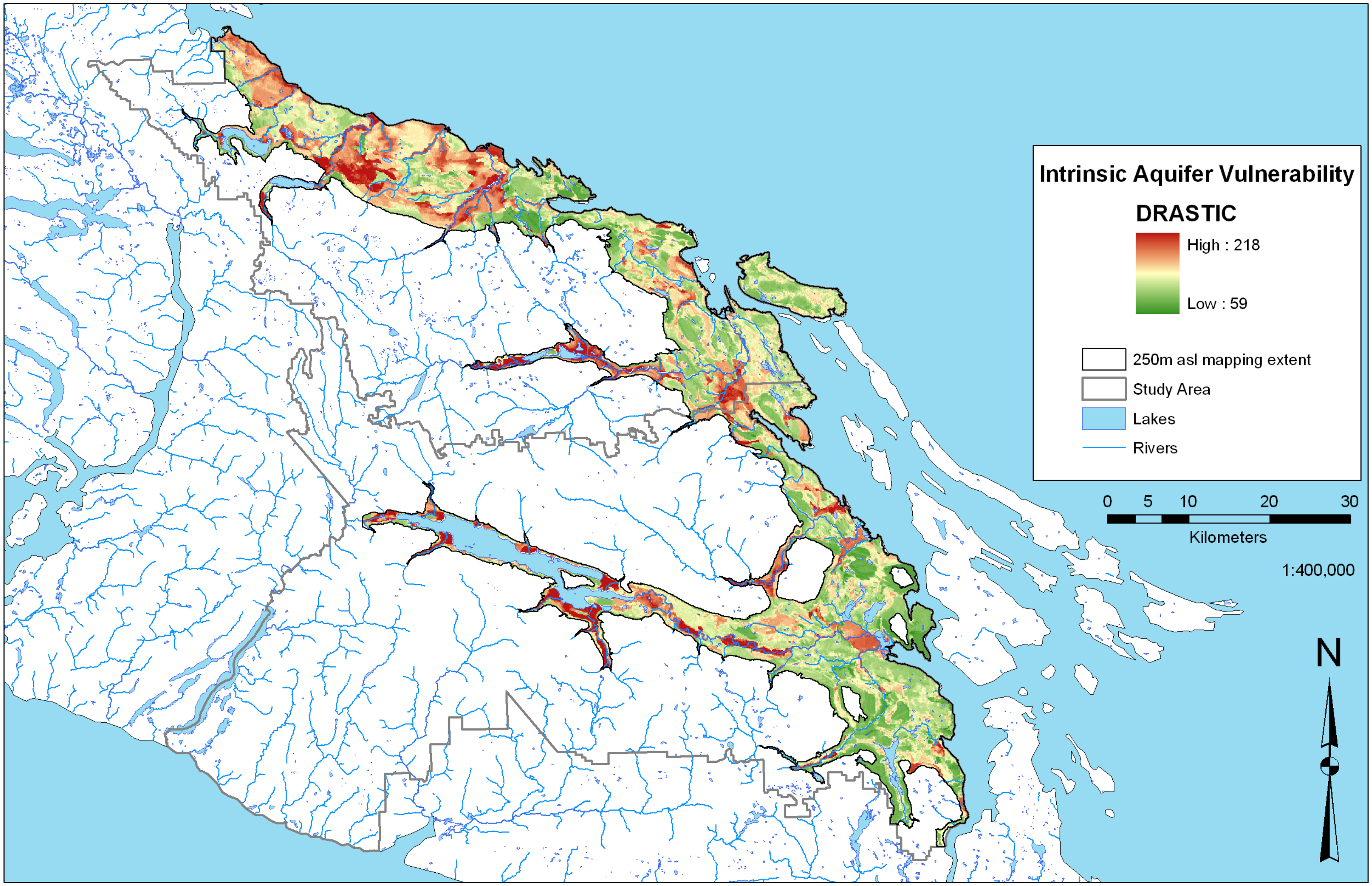
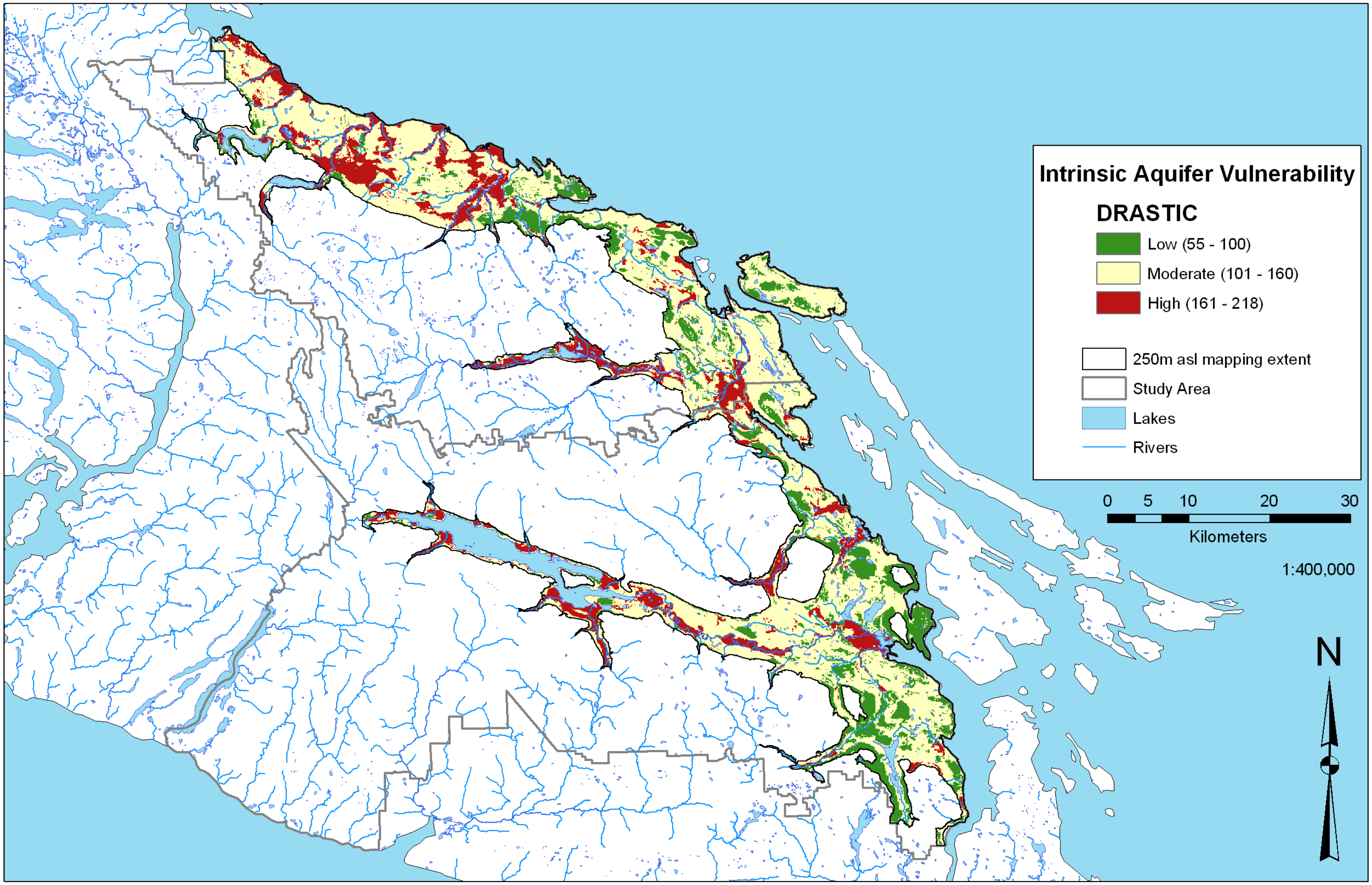


Figure 6.2 Intrinsic aquifer vulnerability map for the Regional District of Nanaimo and Cowichan Valley Regional District grouped in three classes



6.1. Assumptions and Limitations

The maps in Figures 6.1 and 6.2 show a regional representation of intrinsic vulnerability and do not reflect local conditions. Also, the intrinsic vulnerability map for this area shows the vulnerability of the uppermost aquifer only. The following assumptions and limitations further highlight the regional nature of this intrinsic vulnerability map, and emphasize that these maps do not reflect specific local conditions.

Aquifer Delineation

The DRASTIC map represents the vulnerability of the main uppermost aquifer, as shown in Figure 5.3. The study area contains many shallow (e.g. dug) wells, which may tap into small pockets of water bearing material and perched water tables overlying the main aquifer of interest for this study, specifically over low vulnerability confined and bedrock aquifers. Although these pockets may be widespread, most wells in these areas provide water on a domestic scale, rather than regionally. The goal of this project was to determine the vulnerability of the main, developed aquifers rather than of the uppermost available water. The vulnerability of these areas would likely be higher than the underlying main aquifer due to their shallower water depth and possible lack of confining layer.

In areas of mapped confined aquifers, it is possible that the confining layer is not laterally continuous and has windows into the aquifer below. Again, areas with this condition are not captured by the final vulnerability map.

Figure 6.3 shows all wells identified in the WELLS database as being dug, along with the distribution of mapped confined and bedrock aquifers, and the vulnerability. There are a number of locations with groups of dug wells in low vulnerability areas which may indicate more extensive use of these overlying water bearing units. It is unknown how many of these dug wells are still in use, as well as the number of additional dug wells not reported in the WELLS database.

It is difficult to know if potential aquifers in the unmapped areas are confined or unconfined. To be conservative, unmapped surficial aquifers were considered to be unconfined, and unmapped bedrock aquifers were considered to be partially confined. It is possible that some of these unmapped areas are less vulnerable than determined from this study if confining layers are present.

These results provide a first-order screening tool. As more data becomes available over time (e.g. from well records), the existence of an aquifer can be verified and its degree of intrinsic vulnerability could be reassessed.

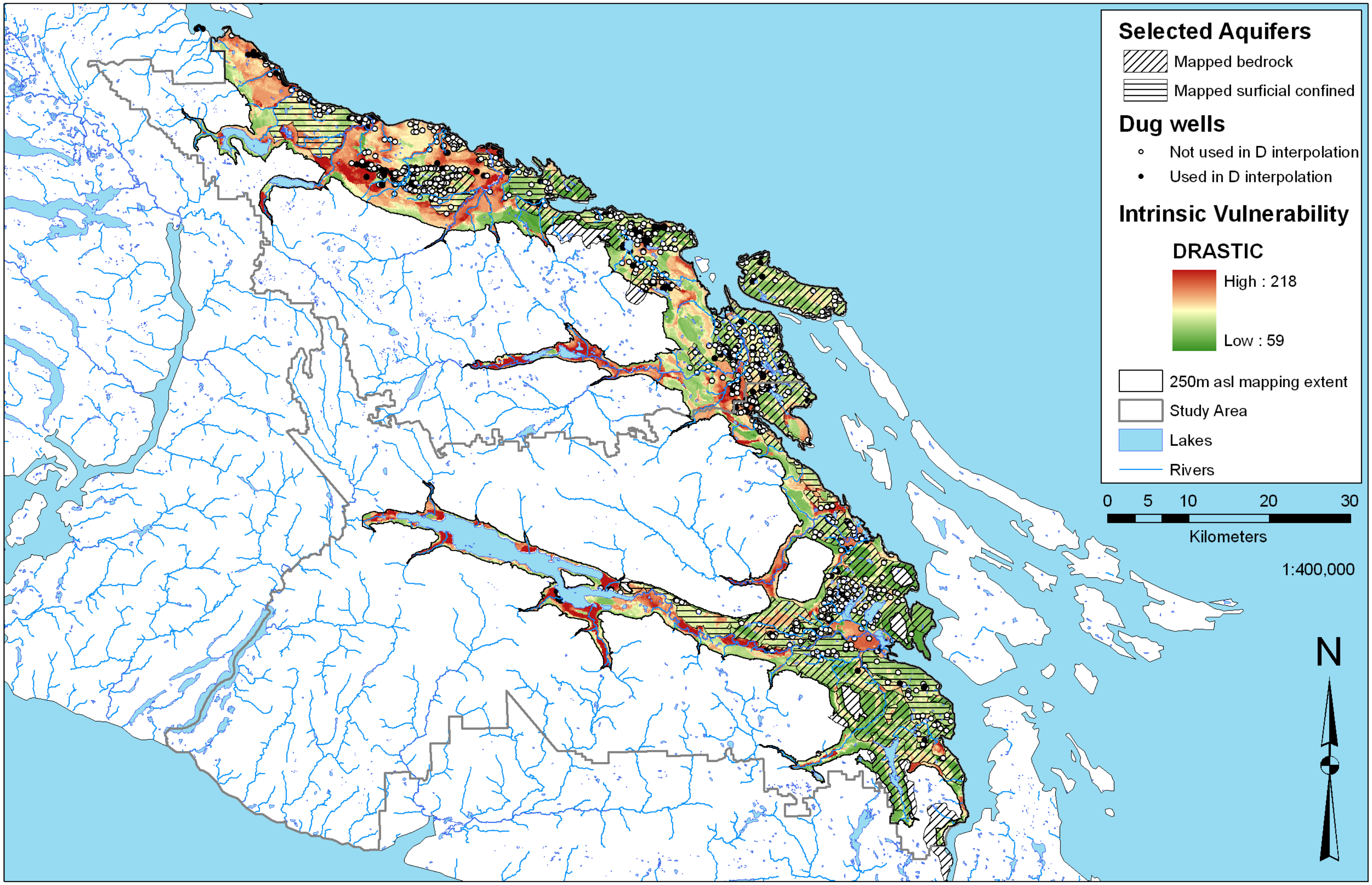


Figure 6.3 Location of dug wells in the study area with mapped confined and bedrock aquifers.

Depth to Water

The interpolated water table surface in areas of unconfined aquifers should be treated with caution, as the water level recorded in each well represents the level when the well was drilled. It is possible that some water levels are slightly lower than the static level, as the water level may not have been given sufficient time to recover following completion. Additionally, the WELLS database contains wells drilled in various seasons over many tens of years, and water levels fluctuate seasonally and annually. However, the depths recorded are often very similar between wells in close proximity, and this gives a certain level of confidence that the surface represents a regional average of the depth to water.

The depth to water map shows a representation of a consolidated water surface and is not strictly the depth to the regional water table or the depth at which water is first encountered. In areas where the uppermost aquifer is unconfined or partially confined, the map represents the depth to the water table. In areas where the uppermost aquifer is confined, the map is a reflection of the depth to the top of the aquifer. Perched water tables or small pockets of water bearing material overlying confined surficial and bedrock aquifers are not evaluated.

Many areas of the interpolated depth to water map (Figure 5.6) have a deep water table (+30.5m) and low rating of 1. These areas are mainly topographic highs with no well data with which to map the depth to water near the top of the high. Consequently, the interpolated water elevation surface cut through the bottom of the high, having no data to 'pull up' the water elevation. The depth to water parameter could be updated as more well information becomes available for these areas.

Recharge

Using a percent of precipitation to map the recharge parameter provides a regional estimate of recharge, not reflective of local conditions. Recharge is a highly spatially variable parameter that is difficult to measure regionally (Liggett 2008, Scanlon et al. 2002, Hendrix and Walker 1997). Local recharge and discharge areas are not explicitly accounted for with this method. Local mapping of recharge and discharge areas would further refine this parameter.

Aquifer Medium

The uppermost texture from the terrain map polygons were used to rate the aquifer medium in areas unmapped by the BC Aquifer Classification System, and with no well data with which to map the overburden thickness. The terrain map polygons attributes contain a lengthy code describing the terrain of that polygon. The only information on thicknesses of material types is the difference between a blanket

(>1m) or a veneer (<1m) of sediment. If the surficial aquifer is deeper, or is part of a layered system, the selection of the uppermost material from the terrain map may not be representative of the actual aquifer medium. With this method it is also possible to have clay aquifers, simply due to the uppermost surficial material, whereas it is most likely that the aquifer is below these materials. Without the aid of local field data or well data it is difficult to determine what the actual aquifer material is. Fortunately, the 250 m asl mapping extent eliminates most of areas where the aquifer material was inferred from the terrain map, resulting in a limited effect on the vulnerability.

All bedrock types were rated low for both the *A*, *I*, and *C* parameter. As shown on the Gulf Islands and in the WELLS database, it is possible to have highly productive bedrock wells which get water from high transmissivity fracture networks. Areas on the land surface which provide a conduit to these fracture systems are highly vulnerable; however, as shown in Section 5.9 more detailed (field) study must be done in order to evaluate the actual effect of fracture flow on Vancouver Island.

Impact of the Vadose Zone

All mapped confined aquifers were assigned a rating of 1, according to the method outlined by Aller et al. (1987). This does not imply that the confining layer is impermeable, nor does it imply that the level of protection offered by the confining layer is constant across the entire aquifer: all of the confining layers vary in thickness throughout the study area. This low rating simply indicates that the confining layer offers more protection to the aquifer relative to the other materials in the study area.

As with the aquifer medium parameter, the uppermost texture from the terrain map was used to represent the vadose zone material. It is possible that the uppermost texture is not the dominant vadose zone texture, but there is a lack of regional scale stratigraphy that would allow for the identification of the most influential vadose zone material. Unlike the *A* parameter, the terrain map was used for all surficial aquifers within the study area, therefore it affects a much larger area within the 250 m asl mapping extent.

Hydraulic Conductivity

Hydraulic conductivity of subsurface material can vary widely. It is assumed that the transmissivity values obtained from the consulting reports are representative of the aquifers in the study area. It is also assumed that the pumping test and analysis was performed correctly.

The use of well-screen length for effective aquifer thickness for the determination of conductivity from transmissivity inflates the conductivity values since the screen length is often thinner than the aquifer. Although the exact values of hydraulic conductivity may be overestimated, from a vulnerability perspective this method still allows the identification of the *relative* vulnerability. The average hydraulic conductivity values for each of the formations of the mapped aquifers may change if 1) more pumping test data were collected from other reports, and 2) if the pumping tests were all re-analysed in a consistent manner.

The average hydraulic conductivity measured in wells completed in aquifers that consisted of Vashon Sediments suggested an anomalously high hydraulic conductivity for this unit. Typically the Vashon Sediments consist of tills which form confining layers in the study area; although there are pockets of coarser grained sand and gravel which can produce usable quantities of water locally. It is likely that wells identified as being in aquifers composed of the Vashon Sediments have targeted these more productive layers, meaning that the average hydraulic conductivity (Table 5.8) is not representative of the entire Vashon Sediment unit. Additionally, the small number of wells (only 6) or errors in the aquifer material identification could also contribute to the anomalous hydraulic conductivity for these wells. In other words, our data set is biased towards higher hydraulic conductivities in units which more frequently form aquitards (or confining layers). The high rating (10) of aquifers consisting of the Vashon Sediments is therefore very conservative, and it may be possible to lower the rating as more information becomes available.

DRASTIC Intrinsic Vulnerability Map

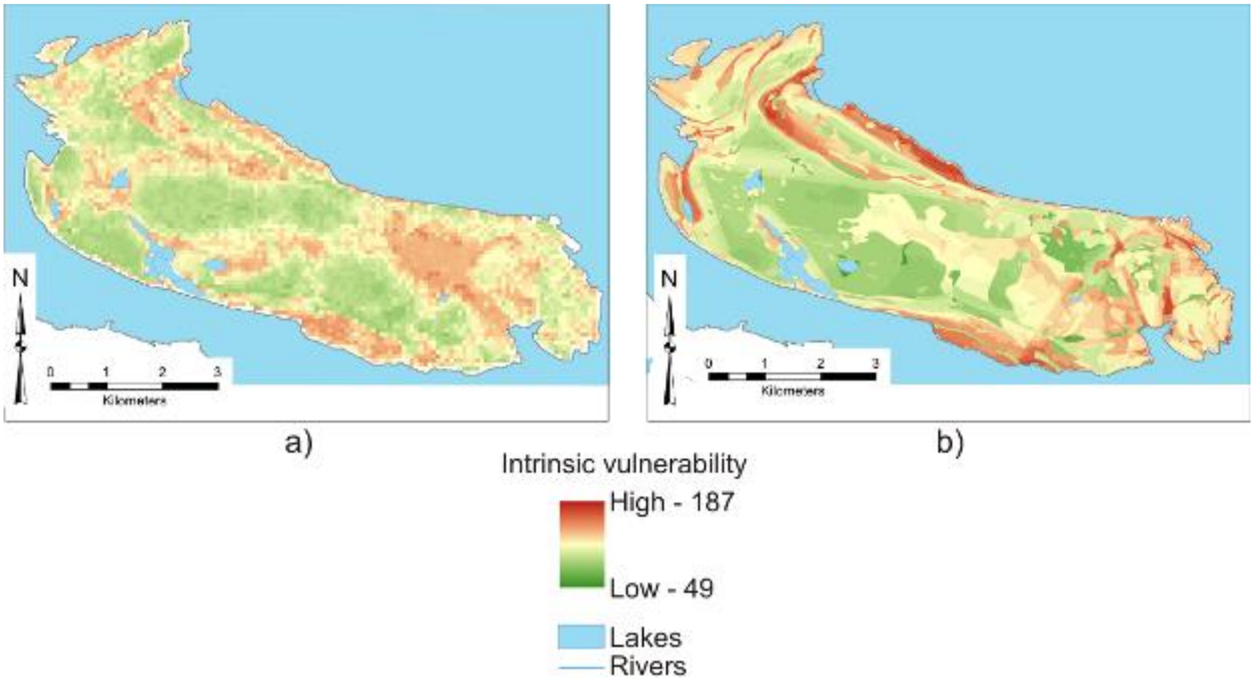
All of the above assumptions and limitations contribute to the uncertainty of the final vulnerability map and highlight the regional applicability of this map. The vulnerability map is to be used as a regional screening tool only, and is not meant to support site-specific decisions. This map provides an invaluable tool to guide the level of investigation necessary for a particular area based on the relative vulnerability category, but is not meant to replace site specific investigation. A low vulnerability does not mean that there is no risk of contamination; it simply means that the geology and hydrogeology of the area provides more natural (or intrinsic) protection to the groundwater resources. One must look at the land use activities and potential hazards associated with such activities to predict the likelihood of contamination. Additionally, as discussed there may be a perched water table or small pockets of water bearing material that may overly the main aquifer in an area. The vulnerability of these areas is not captured by the analysis described in this report.

6.2. Gabriola Island: Current Study vs. Denny et al. (2007)

Gabriola Island is one of the most populated Gulf Islands. It is part of the Regional District of Nanaimo and was included in this study area. The intrinsic aquifer vulnerability was previously mapped on Gabriola Island as part of a study mapping the Gulf Islands (Denny et al. 2007). The vulnerability maps from both the 2007 study and the current study are shown in Figure 6.4. While overall both maps exhibit generally similar patterns in the distribution of vulnerability some differences in vulnerability between maps are due to differing methods used to map each DRASTIC parameter, particularly the *R*, *S*, and *I* parameters, and the incorporation of the fractured media parameter into the 2007 study. The linear features in Figure 6.4b are a result of the incorporation of the *Fm* parameter. Additionally, the *Fm* parameter is assigned a weight of 3, therefore the range of possible vulnerability values is extended from 230 to 260 (total range 23-260). The 2007 study was focused solely on the Gulf Islands and is therefore more representative of the local conditions on the Gulf Islands, including Gabriola; whereas, the vulnerability mapping for the current study was performed on a regional scale, with the methods being applicable to the rest of Vancouver Island.

Figure 6.4 DRASTIC intrinsic vulnerability from a) the current study, and b) Denny et al. 2007.

Note: Vulnerability range for current study was 79 to 154, and in 2007 study was 49 to 187, both maps are depicted using the same colour scale.



7.0 CONCLUSIONS AND FUTURE WORK

Intrinsic aquifer vulnerability, based on the natural properties of the land and subsurface, was mapped for the Regional Districts of Nanaimo and Cowichan Valley along the east coast of Vancouver Island. The common indexing method, DRASTIC, was used to evaluate the groundwater vulnerability based on the depth to water, recharge, aquifer medium, soil medium, topography, vadose zone, and hydraulic conductivity. These seven parameters were estimated and rated according to their relative intrinsic vulnerability, and the ratings were combined to produce the final DRASTIC map.

Continuing work by the members of the VMP includes the expansion of the intrinsic vulnerability mapping to the rest of Vancouver Island. The extent of this mapping will be limited by the availability of water well data, similar to that faced in the study area, unless a new method is developed to determine the *D* and *S* parameters. Work has already begun on a multivariate regression statistical model, developed and validated in areas with well data, to be applied to regions of Vancouver Island with no well data. While the results have a greater margin of error than the interpolated well data, the results so far suggest that the method shows promise. The absence of digital format soils mapping across the northern part of Vancouver Island will require the exploration of other datasets to determine the *S* parameter. The data needed to map the other parameters are available and can be completed using the methods described in this document.

As of Fall 2009, the preparation of a guidance document was underway to provide direction as to how the vulnerability map may be used by practitioners by drawing on examples of uses in other jurisdictions and through consultation with local regional planners.

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