Technical Summary of Intrinsic Vulnerability Mapping Methods for Vancouver Island

Vancouver Island Water Resources Vulnerability Mapping Project – Phase 2

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Executive Summary

The Vancouver Island Water Resources Vulnerability Mapping Project (VMP) was initiated in 2006 by the Vancouver Island Watershed Protection Steering Committee, with a goal of improving land-use decision-making tools concerning the preservation of groundwater quality. The VMP is a collaborative project between the BC Ministry of Environment, Vancouver Island University, Natural Resources Canada, and the Vancouver Island Health Authority. It was determined that intrinsic vulnerability maps would be developed to characterize the vulnerability of aquifers to contamination. Effective tools for decision-makers, these vulnerability maps identify where aquifers are vulnerable to contamination from various high risk land-use activities.

The DRASTIC methodology developed by the U.S. Environmental Protection Agency was used in the pilot study to complete intrinsic groundwater vulnerability mapping for two of the seven regional districts on Vancouver Island – Nanaimo (RDN) and Cowichan Valley (CVRD). This methodology identifies seven parameters that influence groundwater vulnerability, each represented by a letter in the DRASTIC acronym: D – Depth to water, R – net Recharge, A – Aquifer medium, S – Soil medium, T – Topography, I – Impact of the vadose zone, and C – hydraulic Conductivity. All parameters are combined using an equation to determine areas of high, moderate, and low aquifer vulnerability.

The pilot study was completed in 2009, and work began on phase 2 of the VMP with two primary objectives. The study area was expanded to derive intrinsic vulnerability maps for all regional districts of Vancouver Island, and many of the manual processes used to complete the pilot study analysis were automated. Although the specific processes varied, the methodology used to complete the phase 2 analysis was similar to the pilot study. Two notable exceptions include the use of terrain mapping in place of soil surveys, and the assumption that the upper-most surficial aquifers on Vancouver Island aquifers may not be truly confined.

Phase 2 of the VMP used many of the same datasets as the pilot study to complete the intrinsic vulnerability analysis. Again, key datasets included the BC WELLS database, and aquifer maps provided by the BC Ministry of Environment. Terrain mapping was also an essential dataset, as digital soils mapping was not available for the entire island. As with the pilot study, the phase 2 analysis was completed on a regional scale, for all seven of the Vancouver Island regional districts.

Results of the phase 2 intrinsic vulnerability analysis indicate that surficial aquifers represent moderate to high intrinsic vulnerability due to the lack of consistent confining layers and the resulting increased permeability of the vadose zone, in addition to higher aquifer media and hydraulic conductivity ratings, and the relatively shallow depth to water. Bedrock aquifers generally have low intrinsic vulnerability, due to their low aquifer media, vadose zone and hydraulic conductivity ratings, and their greater depth to water.

This document details the methodology used to produce intrinsic vulnerability mapping for all regional districts of Vancouver Island. However, because the phase 2 analysis was largely based on methods used to complete the pilot study, this document focuses on the differences used to complete the phase 2 assessment. It should be used in conjunction with the pilot study report (Liggett and Gilchrist, 2010), to update the vulnerability maps in the future.

Acknowledgements

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1.0 INTRODUCTION

In 2006, the Vancouver Island Region Watershed Protection Steering Committee initiated the Vancouver Island Water Resources Vulnerability Mapping Project (hereafter referred to as the 'VMP'). The goal of the VMP was to develop a GIS-based mapping tool to aid in the improvement of land-use decision-making, with specific interest in protecting groundwater quality. Initially, the VMP focused on a pilot study area to characterize the vulnerability of groundwater to contamination (Liggett and Gilchrist, 2010). Using the DRASTIC method, the VMP developed intrinsic vulnerability maps for the Regional District of Nanaimo (RDN) and the Cowichan Valley Regional District (CVRD).

DRASTIC is an established aquifer vulnerability mapping methodology, developed by the U.S. Environmental Protection Agency (EPA) (Aller et. al, 1987). This method defines seven parameters that contribute to intrinsic aquifer vulnerability, each is represented by a letter in the DRASTIC acronym; D – Depth to water, R – net Recharge, A – Aquifer medium, S – Soil medium, T – Topography, I – Impact of the vadose zone, and C – hydraulic Conductivity. These seven parameters are then combined using a weighted sum equation to determine the overall intrinsic vulnerability.

The primary objective of phase 2 of the VMP is to expand the work of the pilot study to complete intrinsic vulnerability mapping for the remaining five regional districts of Vancouver Island. These include the Capital Regional District (CRD), the Alberni-Clayoquot Regional District (ACRD), the Comox Valley Regional District (CxVRD), the Strathcona Regional District (SRD), and the Regional District of Mount Waddington (RDMW), in addition to the RDN and CVRD. The second objective of phase 2 is the automation of the manual mapping processes used to complete the pilot study. Because phase 2 is based on the methodology developed during the pilot study, the information in this report is supplemental to the "Technical Summary of Intrinsic Vulnerability Mapping Methods in the Regional Districts of Nanaimo and Cowichan Valley" (Liggett and Gilchrist, 2010) and focuses specifically on differences in both the methodology used and results obtained between the pilot study and phase 2.

Automation of processes in the phase 2 analysis was important for a number of datasets, including preparation of the BC WELLS database and the terrain maps. Automation greatly reduced the amount of time required to complete error checking of the BC WELLS database and data extraction from the terrain map. It also enabled more data to be extracted from the terrain map for use in the A, S, I, and C parameters. The work of the pilot study was used to confirm the accuracy of automating the work during phase 2.

Additional changes in the phase 2 analysis included using the terrain mapping in place of soil surveys to rate soil medium due to the lack of digital soil mapping for northern Vancouver Island, and the incorporation of hydrogeological parameter data extracted from hydrogeological reports from regional districts in the phase 2 study area. Furthermore, it was assumed in this analysis that all surficial aquifers are unconfined.

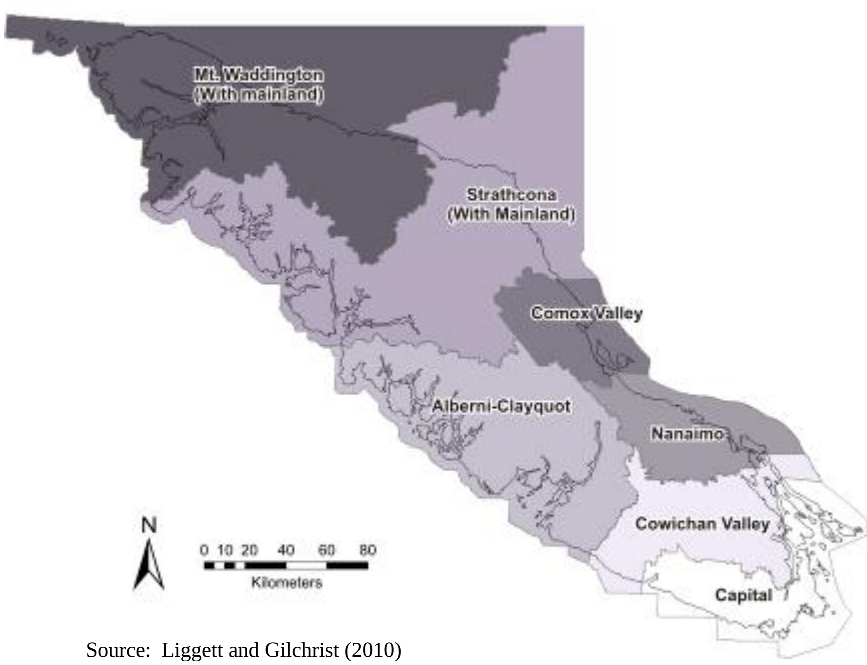
Like the pilot study, the vulnerability maps are completed at a regional scale, with the objective of providing communities, planners, and policy makers with a tool to aid in the process of decision-making for various land-use issues that have the potential to affect groundwater quality. Although we are not attempting to address causes of aquifer pollution or suggest land-use recommendations at this time, the vulnerability maps will aid in numerous groundwater management issues, including "sustainable development planning, identification of sensitive areas, planning of monitoring strategies, and focusing remediation efforts" (Liggett and Gilchrist, 2010). There is potential for future interaction between the VMP and local planners, to identify specific pollution risks and develop land-use recommendations at a more local scale.

2.0 STUDY AREA

The VMP pilot study completed intrinsic vulnerability maps for two of the seven regional districts of Vancouver Island: the RDN and CVRD. Phase 2 of the VMP has an expanded study area which includes all seven regional districts of Vancouver Island, and several islands (Malcolm, Cormorant, Quadra, Cortez, Hornby, Denman, and Gabriola Islands) (Figure 2.1).

Although the study area has been expanded and now includes well records for over 24,000 wells, this data is only available for populated areas. As a result, the final vulnerability mapping is limited in extent, similar to the final output of the pilot study. This is discussed in greater detail in Section 5.2.

Figure 2.1 Regional districts on Vancouver Island



Source: Liggett and Gilchrist (2010)

3.0 DRASTIC

Phase 2 of the intrinsic vulnerability mapping was completed using the DRASTIC methodology as discussed in Liggett and Gilchrist (2010). The seven parameters were assembled and combined using a weighted sum equation to produce the final intrinsic vulnerability map (Aller et. al, 1987). The pilot study also examined the possibility of including fractured media (Fm) in the analysis, similar to the Gulf Islands study (Denny et al., 2007). Due to lack of data, Fm was not considered in the final intrinsic vulnerability analysis for the pilot study, and was therefore not included in phase 2 of the VMP.

4.0 DATA SOURCES

Phase 2 of the VMP used similar datasets to those used in the pilot study (Table 4.1), with the exception of lineaments. However, preparation of the data for use in the intrinsic vulnerability analysis was previously completed for the pilot study area of interest only. As a result, substantial effort was required in phase 2 of the study to prepare the BC WELLS database, the compiled Vancouver Island Terrain map dataset, and the hydrogeological report compilation and data extraction for use in the intrinsic vulnerability analysis.

Table 4.1 Data sources for vulnerability mapping in the phase 2 study area. D = depth to water, R = recharge, A = aquifer medium, S = soil medium, T = topography, I = impact of the vadose zone, C = conductivity

Data Set	Source	Scale	Date	Description	Use in DRASTIC
Digital Elevation Model	BC Integrated Land Management Bureau	25m grid		Digital elevation model of the study area	*D*, *T*, visual
Wells	BC WELLS database	N/A	Dec. 2009	Wells from BC database, in Microsoft Access® database	*D*, *A*, *I*, *C*,
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*, *I*, *C*
Precipitation	ClimateBC	400 m grid	2006	Interpolated precipitation data for Vancouver Island	*R*
Aquifer polygons & worksheets	BC MoE	N/A	2007 (polygons) 1995-2004 (worksheets)	Mapped aquifer polygons and aquifer worksheets	*A*, *C*, *I*
Hydrogeological consulting reports	Various	N/A	1963-2007	72 reports on RDMW, ACRD, RDCV, SRD, and CRD areas. Relevant hydrogeologic data was extracted from these reports.	*C*
Terrain map	Forest Renewal BC	1:50K	1975-1983	Compilation of terrain mapping of Vancouver Island. Texture included in long code. Individual original terrain maps are viewable and downloadable from http://www.empr.gov.bc.ca/Mining/Geoscience/TerrainandSoilMaps/Pages/IntroductoryMap.aspx	*A*, *I*, *S*, *C*
NTS Grid	Natural Resources Canada	1:50K		National Topographic System of Canada	Terrain map preparation
Census Subdivisions	Natural Resources Canada	1:1,000,000	2008	Census subdivisions used to update regional boundaries, downloadable from http://www.geogratis.ca/geogratis/en/collection/metadata.do?id=36925	Visual
Regional boundaries	RDs and MoE	N/A	N/A	Regional boundaries of RDN and CVRD, including electoral districts.	Visual

4.1 British Columbia WELLS Database

Phase 2 of the VMP was completed using an updated version of the BC WELLS database, obtained directly from the Ministry of Environment (current on December 01, 2009). This database contains the construction records of over 90,500 wells in BC, all spatially located. Various pieces of information, including lithology intersected by the well and depth to water, are used to complete the upper-most aquifer map, as well as the D, A, I, and C parameters. As with the pilot study, this dataset required considerable preparation prior to use in the intrinsic vulnerability analysis. A number of database errors identified in the pilot study were also addressed in phase 2, using automated processes in place of manual review. Error checking was completed in two stages: first for the WELLS lithology table, followed by a review of errors in the WELLS attribute table. The erroneous records were extracted and returned to the MoE for review.

Well lithology was used to verify bedrock depths recorded in the WELLS attribute table. This information was then used to assemble the upper-most aquifer map, necessary for the completion of the D, A, I, and C parameters. Well lithology contains information about the lithological units encountered during the well drilling process. These units are listed in sequential order, starting at the top of the well. Each unit has a 'from depth' and a 'to depth;' the 'to depth' of one unit should match the 'from depth' of the unit below. Lithology data was available for 23,713 of 24,366 wells in the phase 2 study area. Using multiple queries in Microsoft Access®, erroneous records as listed in Table 4.2 were identified and removed from the lithology table.

Table 4.2 Lithology error checks (listed in order of completion) and codes used to identify invalid lithology records

Lithology Code	Lithology Error Checks	Number of Lithology Records Remaining	Number of Wells Remaining
n/a	Lithology records (BC WELLS)	462,269	87,271
n/a	Study area lithology records (Vancouver Island and additional islands)	125,652	23,713
n/a	Duplicate records removed	125,621	23,713
N	'From' and 'to' depths both zero (lithology records are comments only)	101,382	20,970
Q	Lithology sequencing errors ('to' depth of a unit not equal to 'from' depth of the unit below)	76,929	16,919
T	'From' depths greater than 'to' depth (in the same lithological unit)	76,882	16,910
W	'From' depths greater than well depths	72,011	16,117
M	First recorded 'from' depth not zero (lithology sequences missing for upper layers)	71,334	15,854
P	Previously drilled wells (lithology missing for upper layers)	70,793	15,656

The cleaned WELLS lithology table was then used to create a dataset identifying the depth to first encountered bedrock in the wells. Table 4.3 lists the error checks that were completed in order to produce a clean first encountered bedrock depth dataset, used to complete the upper-most aquifer map. The WELLS attribute table was updated to reflect the revised bedrock depths obtained from the well lithology records.

Additional errors in the WELLS attribute table included unreasonable well depths (greater than 1,200 feet), unreasonable water depths (over 1,000 feet), water depths greater than the total well depth, and duplicate well records. Non-populated values in the well depth, water depth, and bedrock depth fields were also identified. These errors are included in Table 5.1 (Section 5.2). Like the pilot study, errors may still exist in the WELLS database due to inaccuracies of the original data or subsequent data entry/processing.

Table 4.3 Bedrock lithology error checks (listed in order of completion) and codes used to identify invalid bedrock lithology records.

Lithology Code	Lithology Error Checks	Number of Bedrock Lithology Records	Number of Wells Remaining
n/a	Clean WELL lithology	70,793	15,656
n/a	Bedrock lithology selection (all bedrock lithology units)	23,321	10,342
n/a	First encountered bedrock lithology (only the upper-most bedrock lithology unit for each well – one record per well)	10,342	10,342
n/a	All wells encountering bedrock (bedrock wells from WELLS attribute table updated with data from first encountered bedrock lithology)	n/a*	24,363
H	Unconfirmed zero bedrock depths in WELLS attribute table (no lithology data available to verify 0 depths)	n/a*	13,761
I	Invalid bedrock depths in WELLS attribute table (well not a valid bedrock well based on bedrock lithology selection)	n/a*	13,460
J	Unconsolidated materials below last sequence of bedrock	n/a*	13,073
K	Bedrock depths obtained from lithology 'comments' (valid bedrock depths, obtained from records with from and to depths both zero – code 'N' in Table 4.2)	n/a*	13,297

* Bedrock lithology records are no longer used once the WELLS attribute table is updated with the data from the first encountered bedrock lithology dataset.

4.2 Compiled Vancouver Island Terrain Mapping

Data from the terrain map (refer to Table 4.1) provides the basis for four of the seven parameters used in the DRASTIC method (A, S, I, and C). Preparation of this dataset was completed during the pilot study, but only to a very limited extent. For example, extraction of specific data from terrain polygon labels was completed for the pilot study area only, and did not account for multiple components or stratigraphic layers within a single terrain polygon. A number of additional issues were identified during the pilot study, including edge-matching inconsistencies, sliver polygons, and non-populated fields. It was determined that the phase 2 analysis would benefit from a more accurate and complete dataset, particularly from the stratigraphic layer information provided in the terrain polygon labels.

The first task in preparing the terrain map dataset for use in the phase 2 analysis was the documentation of edge-matching inconsistencies along all mapsheet boundaries. The terrain map is a compilation of multiple mapsheets merged into a single dataset. As a result of this process, many terrain polygons split by mapsheet edges have been labeled differently on either side of the mapsheet edge. Classification of polygons using the existing surficial material, surface expression, texture, and geomorphological process values allowed for visual inspection along each boundary. Where inconsistencies occur between each side of polygons split by a mapsheet edge, the different values on each side were recorded into a Microsoft Excel® spreadsheet.

Results of this procedure expose two areas where split polygons are significantly different along multiple connecting mapsheet boundaries. These distinctions are reflected in the soil medium parameter (Figure 5.7), which is based solely on the terrain map. Comparison with the original mapsheets confirms that the continuous variation along these boundaries results from the original terrain maps being completed at different times, or by different authors, using different standards. Accuracy of the original terrain maps cannot be confirmed; consequently, edge-matching inconsistencies were not corrected and still exist in the terrain map dataset.

Compilation of the full terrain map also resulted in sliver polygons along mapsheet boundaries. These narrow polygons, less than 1 hectare in size, were merged with the neighbouring polygon that had the largest area.

A third issue with the terrain map was non-populated values in the “label” field. These records were updated prior to any further analysis, as the terrain label provides values used to assemble the A, S, I, and C parameters. Referring to the original terrain maps (Appendix 1, Newton, 2010) and the associated documentation defining the interpretation of digital labels (Appendix 2, Newton, 2010), the empty values were updated to reflect the terrain polygon label, or whether the terrain polygons were actually lakes, small offshore islands, rivers, oceans, or part of an estuary.

The fourth requirement to prepare the terrain map for use in the intrinsic vulnerability analysis was the parsing of the terrain polygon label. This single value is composed of a number of individual characteristics for up to three components of a terrain polygon. If multiple components exist, they are combined into a single composite label, with the most extensive component listed first, followed by the less extensive components (Howes and Kenk, 1997). In addition, the terrain polygon label also identifies up to three stratigraphic layers within each component. For the purposes of this study, only three characteristics are of interest: texture, surface material, and surface expression. Each of these three characteristics from the nine possible components were extracted from the full terrain polygon label and recorded separately, using VBA scripts.

Where the terrain map was used to provide ratings for the A, I, and C parameters, the pilot study was only able to utilize information from the upper-most stratigraphic layer. The comprehensive parsed dataset produced in phase 2 resulted in the more accurate representation of aquifer medium and vadose zone materials for use in the A, I, and C parameters. Soil medium was represented by the upper-most texture value, but the A, I, and C parameters were able to utilize information from the lower stratigraphic layer where it was available.

For a detailed methodology of the processes used to prepare the terrain map for the vulnerability analysis, refer to Newton (2010).

4.3 Hydrogeological Report Compilation

A compilation of hydrogeological reports was completed for the RDN and CVRD during the pilot study, resulting in the extraction of hydraulic conductivity data from 71 reports (Liggett and Gilchrist, 2010). Phase 2 extracted data from 72 additional reports that were obtained for the additional five Vancouver Island Regional Districts; 8 for the RDMW, 6 for the ACRD, 17 for the CxVRD (Comox Valley), 9 for the SRD, and 32 for the CRD. Hydraulic conductivity (K) was provided in 12 reports, and many others reported values of transmissivity (T) and/or specific capacity (SC).

As with the pilot study, the data extracted from these reports was used to characterize aquifers within the study area and provide hydraulic conductivity ratings for the C parameter (Section 5.8).

5.0 METHODS

As the methodology used to prepare the intrinsic vulnerability maps has been previously discussed in Liggett and Gilchrist (2010), this document focuses on processes that differ from the pilot study methodology.

Intrinsic vulnerability mapping completed by the pilot study was limited to areas below 250 m asl, due to a lack of well data above this elevation. Beyond the pilot study area, there is a large unpopulated area without well data below 250 m asl. Therefore, the final mapping extent for phase 2 was changed to include all areas within 5 kilometres of available well data. Comparison of this extent with the pilot study area of interest shows that it is similar.

5.1 Aquifer Delineation

The intrinsic vulnerability analysis is applied to the upper-most aquifer in any given area. Consequently, determining the nature of the upper-most aquifer is an important part of the analysis. The upper-most aquifer map was created for the expanded study area using the same processes documented in Liggett and Gilchrist (2010). The same six aquifer types recognized for the pilot study were utilized in phase 2. Mapped aquifers refer to aquifers classified using the BC Aquifer Classification system (Berardinucci and Ronneseth, 2002).

Six types of aquifers were recognized for this study, as shown in 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

Where mapped aquifer polygons are available, the upper-most mapped aquifer was identified and confinement was determined from the aquifer worksheets. Where mapped aquifer data is not available but there is sufficient well data, the upper-most aquifer is identified using overburden thickness. The depth to first encountered bedrock from the WELLS database (Section 4.1) was used to interpolate the overburden thickness. The resulting map illustrates the thickness of unconsolidated surficial material above bedrock (Figure 5.1).

The overburden thickness data was then examined to determine the minimum thickness required to support a surficial aquifer. Aquifers greater than this thickness are classified as surficial; aquifers less than this thickness are classified as bedrock. The critical thickness determined in the pilot study was 10.5 m. The critical thickness determined for phase 2 was 10.45 m (Figure 5.2). At this thickness, 81% of both bedrock and surficial wells were correctly identified in their respective aquifer types. As with the pilot study, the percentage of correctly identified wells increased to over 86% when a 200 m buffer was placed around the classified aquifers.

Lastly, for areas without mapped aquifers or WELLS data, the first encountered surface expression values from the terrain map were used to determine the upper-most aquifers. In areas with a veneer of overburden (less than 1 m thick) underlain by rock, the upper-most aquifer is classified as bedrock. In areas with a blanket of sediment (greater than 1 m thick), the upper-most aquifer is classified as surficial.

Figure 5.1 Segment of the interpolated overburden thickness map, SRD & CxVRD

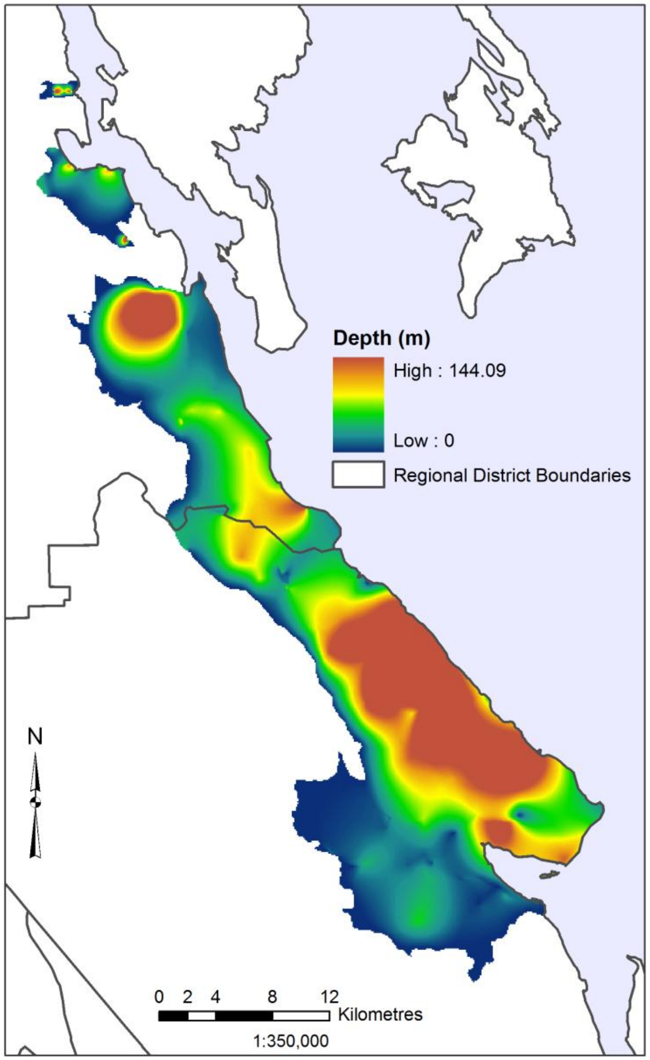


Figure 5.2 Segment of the derived critical overburden thickness map, SRD & CxVRD

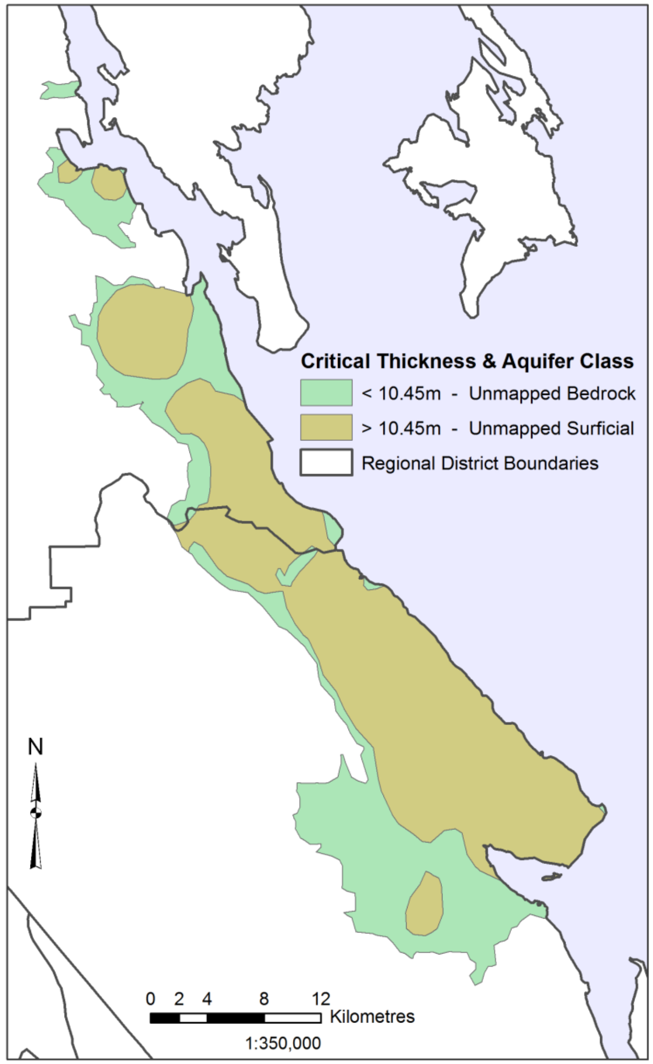
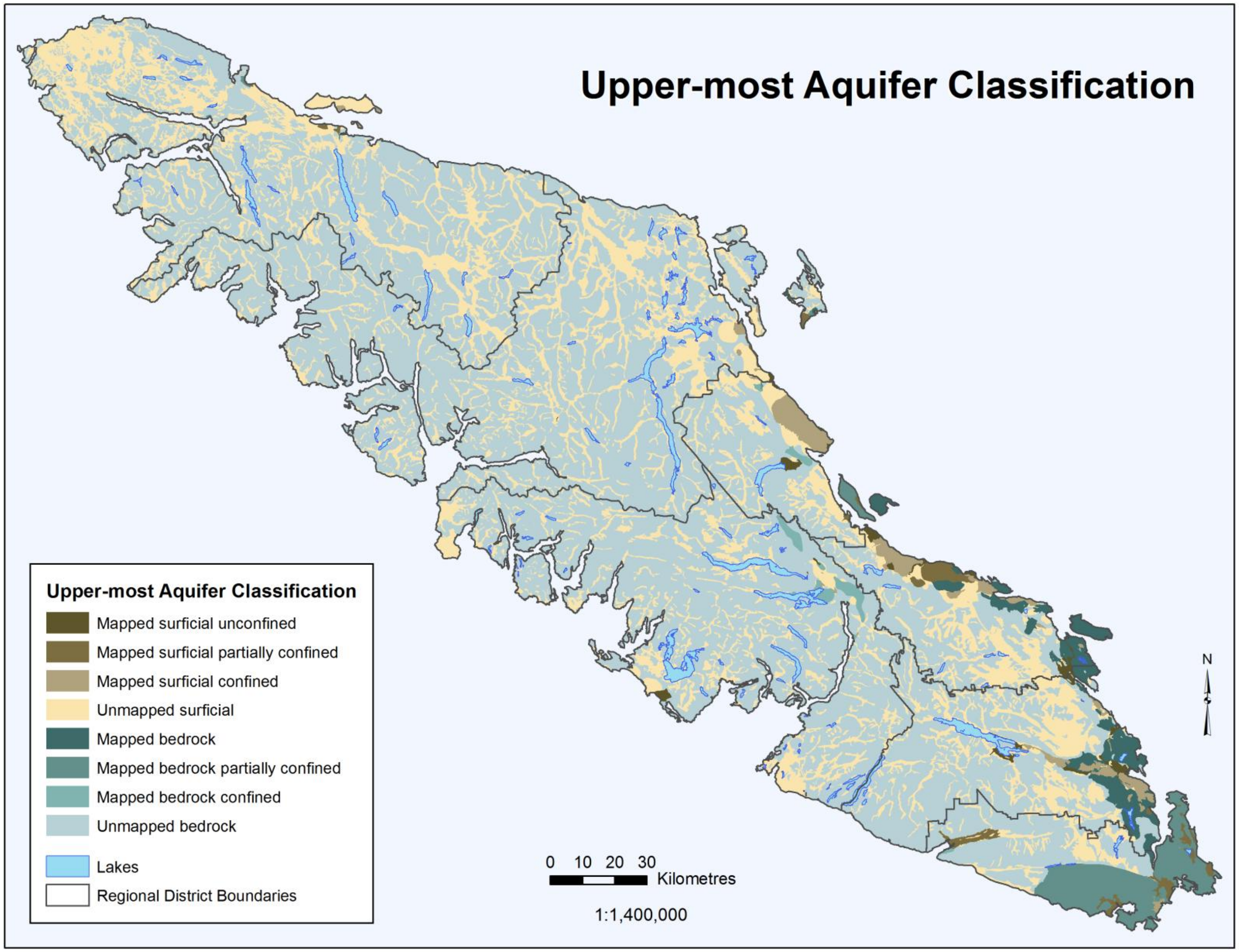


Figure 5.3 Aquifer types within the VMP phase 2 study area. 'Mapped' aquifers refer to those mapped with the BC Aquifer Classification System, and 'unmapped' refers to areas classified by this study.



5.2 Depth to Water

The depth to water parameter completed during the phase 2 vulnerability analysis was based on the same principles discussed in the pilot study, and used wells completed in the upper-most aquifer only. However, due to the automation of tasks that were completed manually in the pilot study, and the assumption that the upper-most aquifers on Vancouver Island are not truly confined, some changes were made to the methodology for phase 2. Confined aquifers may exist below the top-most aquifers, but these are not considered in the DRASTIC analysis. The most significant difference from the pilot study is confinement. The pilot study used the depth to top of aquifer as the water depth where the upper-most aquifer is confined. However, after trying various methods to determine confinement in phase 2, it became evident that either the mapped confined aquifers may not be truly confined, or that the well lithology logs could not support that interpretation. These aquifers were located at shallow depths, and often lacked a consistent confining layer in the lithology logs. As a result, all surficial aquifers were considered to be unconfined or partially confined, and depth to water was represented by the water depth recorded in the WELLS database.

For the pilot study analysis, the lithology logs for wells completed in confined aquifers were manually reviewed to extract the depth to the top of the aquifer, and to determine if the wells are located in the upper-most aquifer. In phase 2, several methods were assessed to automatically determine aquifer confinement. However, none of the methods returned consistent results. Well records containing potential confining layers were identified by using queries in ArcMap® and Microsoft Access® to scan well lithology records. Multiple definitions of "confining layers" were used, including identifying single layers with low hydraulic conductivity (i.e. clay or other fine grained material), and determining the geometric mean hydraulic conductivity of all layers to see if there was a relationship to confinement. In all cases, there was a low correlation between wells meeting the proposed confining criteria and mapped confined aquifers. Less than 45% of all wells within confined aquifers were classified as confined using the different criteria outlined above.

The terrain map was also used to try and determine confinement by examining relationships between known confined, partially confined, and unconfined aquifers, and surficial material and texture. This was completed for both the upper and lower stratigraphic layers. This method also returned inconsistent results and no reliable conclusions could be made about the relationship between confined aquifers, surficial material, and texture.

Reliably determining the degree of confinement of a particular aquifer requires detailed lithological information, groundwater levels and hydrogeological expertise. The quality of well construction records is highly variable and often is not detailed enough to support attempts to automate the process of determining confinement. Therefore, phase 2 of the intrinsic vulnerability analysis has been completed on the basis that all upper-most aquifers are unconfined. This is a more conservative approach to vulnerability mapping, and results in generally higher vulnerability ratings being assigned to aquifers classified as confined in the pilot study (Section 6.0).

Once it was determined that all surficial aquifers would be treated as unconfined, the wells were reviewed to determine whether they were acceptable for use in the depth to water interpolation. As with the pilot study, all wells were assigned a code (Table 5.1) to determine which wells were included in the depth to water interpolation or to record the reason why they were not used in the interpolation. The pilot study list has been updated to include additional scenarios encountered in the phase 2 study. Refer to Liggett and Gilchrist (2010) for additional codes relating to confined wells.

Table 5.1 Well codes used to delineate wells for depth to water interpolation

Well Code	Description
L	No valid lithology log
X	Well location not confirmable (no UTM coordinates provided)
R	Repeated well (two entries for one well)
Y	No reported well depth, zero well depth (zero depths are acceptable if the reported water depth is less than the final depth recorded in well lithology)
F	Erroneous well depths (i.e. greater than 1,200 ft)
Z	No reported water depth, zero water depth
E	Erroneous water depths (i.e. greater than 1,000 ft, or if water depth is greater than well depth, or if well depth is 0 and water depth is greater than the final depth recorded in well lithology)
G	Erroneous bedrock depths (greater than 1,000 ft)
A	Artesian well (flowing)
B	Bedrock well drilled below identified surficial aquifer
S	Surficial well drilled above identified bedrock aquifer
V	Confined bedrock aquifer

Surficial Aquifers

All surficial aquifers, whether mapped or unmapped, were assumed to be unconfined. Accordingly, the depth to water was represented by the water depth recorded in the WELLS database. The wells were reviewed for “errors” and assigned a code to determine whether they were valid for the depth to water interpolation. Errors included bedrock wells in identified surficial aquifers, in addition to the other general WELLS errors listed in Table 5.1.

Bedrock Aquifers

Bedrock aquifers were processed identically to the methods used in the pilot study. All were considered to be partially confined – as a result, any wells with a water level greater than three feet above the bedrock surface were considered confined and removed from the analysis. Also, any surficial wells drilled above identified bedrock aquifers were removed from the analysis.

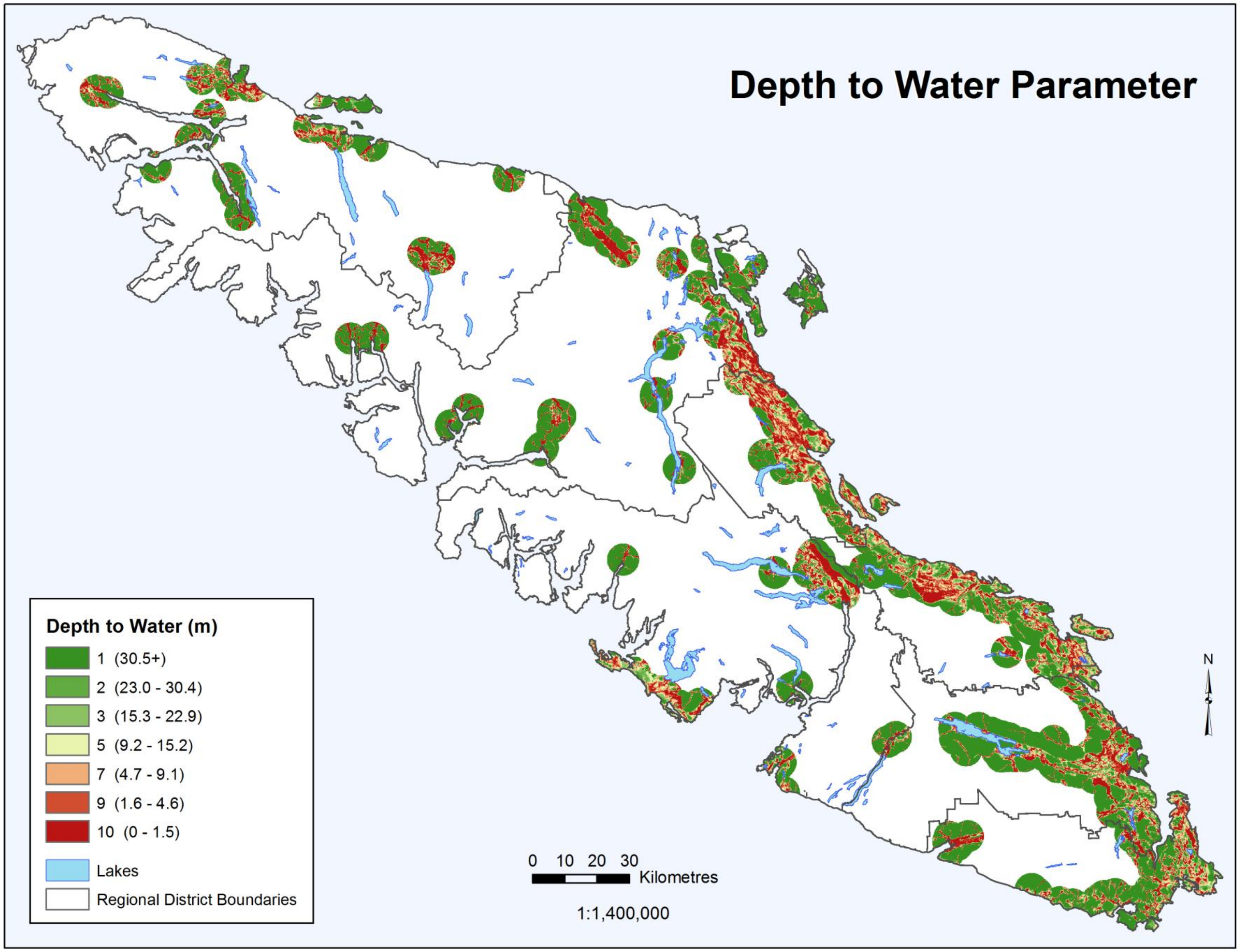
Depth to Water Interpolation

The depth to water interpolation was also completed using the same methodology as discussed in Liggett and Gilchrist (2010). Of the 24,366 wells in the study area, 10,183 were used to interpolate the depth to water parameter. Zero-depth control points were added along rivers and lakeshores, as well as along the entire study area coastline, to ensure the full study area was included in the interpolation. A digital elevation model (DEM) was used to convert the depth to water to water elevation above sea level. The Natural Neighbor method and a 100 m grid cell size were used to interpolate the water elevation. This surface was then subtracted from the DEM to determine depth to water for the entire interpolated area. The depth to water rating table (Table 5.2) used to assign vulnerability ratings followed the original U.S. EPA table (Aller et. al, 1987). Like the pilot study, areas interpolated to be above ground surface were assigned a vulnerability rating of 10 due to their probable shallow depth to water. The distribution of well data limited the extent of the final D parameter (Figure 5.2) to within 5 km of wells used in the interpolation (Section 5.0). As a result, the D parameter restricted the extent of the final vulnerability map (Figure 5.4).

Table 5.2 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	9.2 – 15.2	5
15 – 30	4.7 – 9.1	7
5 – 15	1.6 – 4.6	9
0 – 5	0 – 1.5	10

Figure 5.4 Depth to water parameter, rated according to Table 5.2



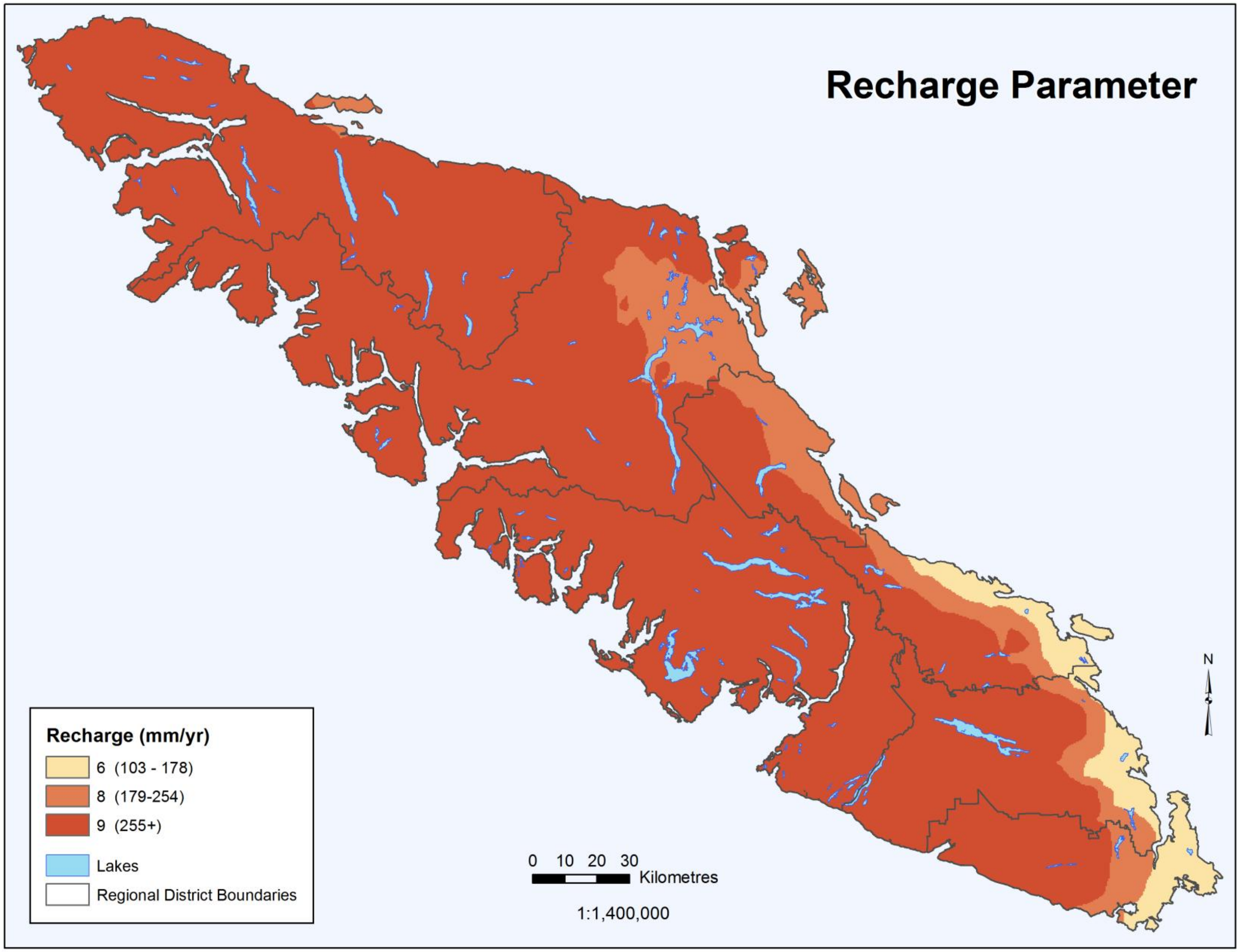
5.3 Recharge

The recharge parameter was completed using the same methodology as discussed in Liggett and Gilchrist (2010). In the pilot study, a monthly water balance was calculated for three watersheds to validate the assumption that groundwater recharge is approximately 15% of annual precipitation. In phase 2, an additional three watersheds were analyzed using the same methodology; Tsolum River, Oyster River (both east coast Vancouver Island), and Gold River (west coast Vancouver Island). From the water balance, an annual surplus of between -12% and +12% of the annual precipitation cannot be accounted for. Where the annual surplus is positive, water likely exits the watershed as groundwater within the floodplain. Where the annual surplus is negative, this suggests that an estimation error has been introduced into the calculation.

Errors are most likely present in the spatial estimate of annual precipitation derived from ClimateBC data, as unsampled areas within each watershed (that are far from a climate station) have a value assigned using an interpolation algorithm. The analysis also suggests that the maximum amount of water entering all forms of temporary storage (i.e. snow, soil and groundwater) is between 13% and 36%. This range is greater than for the three watersheds analyzed during the pilot study (20% - 26%). The low value is likely artificial and should be higher as it is linked to the negative annual surplus (Tsolum River), which is due to an estimation error. The high value is associated with the Oyster River watershed, which has the highest mean elevation (845 m asl) of those studied, and snow accumulation in winter is probably inflating the maximum storage value. Taking these factors into account, the total amount of temporary storage taken up by groundwater within the three watersheds studied during phase 2 are similar to the watersheds analyzed during the pilot study, confirming that recharge is reasonably estimated as 15% of annual precipitation.

Recharge was rated according to the table given in Liggett and Gilchrist (2010). Ratings of 6, 8, and 9 were obtained for the phase 2 study area, the same as for the pilot study, as shown in Figure 5.5.

Figure 5.5 Recharge parameter



5.4 Aquifer Medium

The aquifer medium parameter was also completed using a similar methodology to that discussed in Liggett and Gilchrist (2010). The only change was to the ratings assigned to unmapped surficial aquifers. The pilot study based the ratings assigned to unmapped surficial aquifers on the upper-most texture identified by the terrain map. However, due to the more detailed information provided by the parsing of the terrain map (Section 4.2), phase 2 based aquifer medium ratings on the first encountered texture of the lower stratigraphic layer where possible.

In addition, a more comprehensive rating table was developed for phase 2 (Table 5.3). The pilot study rating table was updated to also include the full range of texture and bedrock geology values encountered in the expanded study area. The rated aquifer medium map is shown in Figure 5.6.

Table 5.3 Aquifer medium and impact of the vadose zone rating table for all of Vancouver Island.

Bedrock Formation	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, lower amphibolite/kyanite grade metamorphic) • Saltspring Intrusive Suite • Buttle Lake Grp (4th Lake Fm, 4th Lake Volcanics) • Island Plutonic Suite • Pacific Rim Complex (Leech River metasedimentary) • Unnamed Cretaceous intrusions • Unnamed Granodioritic, Quartz Dioritic, and Dioritic Intrusions • Clayoquot Plutonic Suite • Catface Intrusions • Mount Washington Plutonic Suite • Metchosin Igneous Complex (Sooke Gabbro, Sheeted Dykes) • Turtleback (Turtleback Fm)	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, fines, sandy fines, gravelly clay, mud	3
• Sicker Grp (Duck Lake Fm, Nitnat 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) • Haro Grp (Haro Fm) • Deadman Bay Grp (Orcas Fm, Deadman Bay 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 (cont.) Aquifer medium and impact of the vadose zone rating table

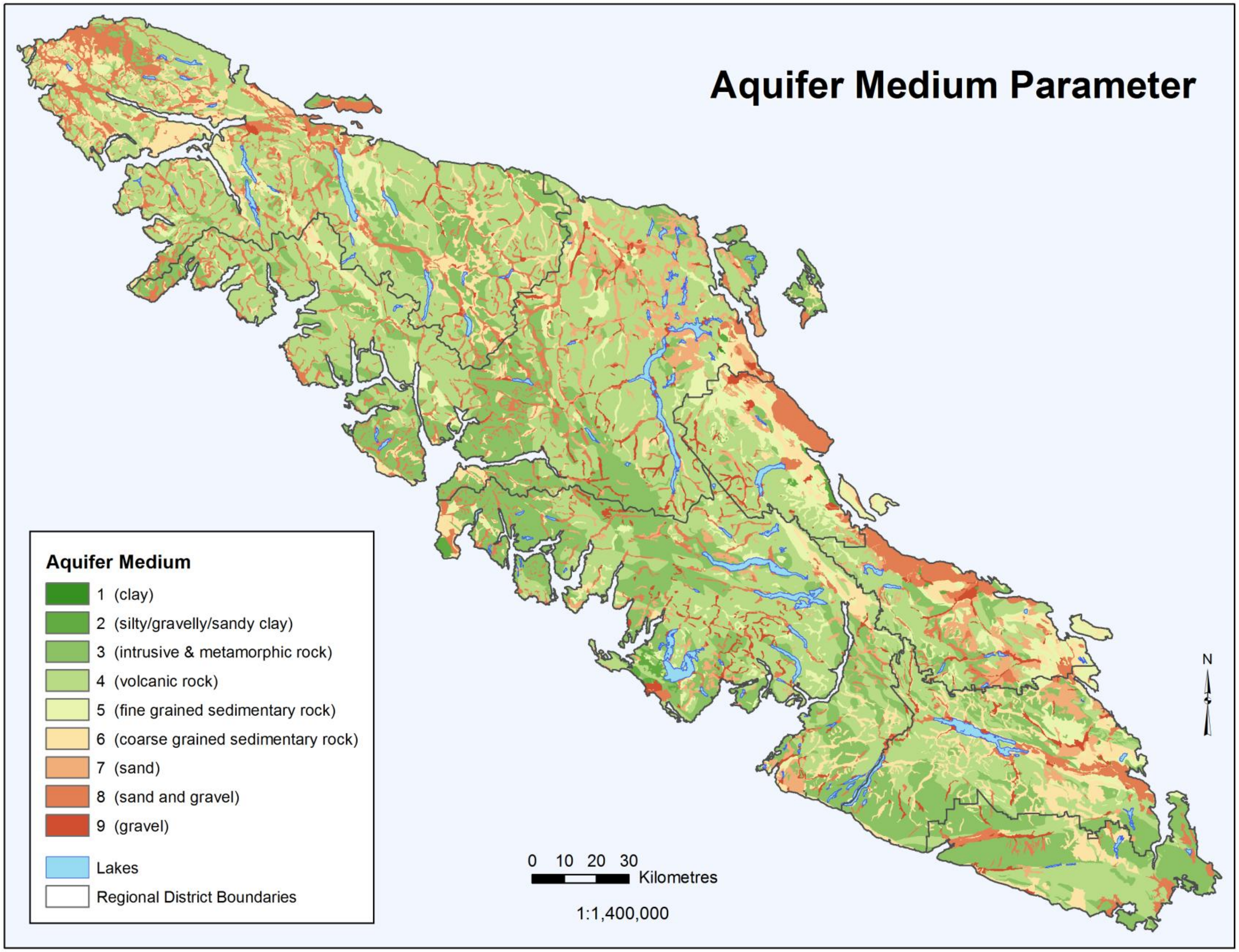
Bedrock Formation	Bedrock Material	Mapped Surficial Aquifer Material	Terrain Map Material	*A* and *I* Rating
• Buttle Lake Grp (Mount Mark Fm) • Vancouver Group (Daonella Beds, Quatsino Fm, Parson Bay Fm, undivided Vancouver Grp, marine sedimentary and volcanic grp) • Bonanza Grp (Harbledown Fm) • Kyuquot Grp • Nanaimo Grp (Sidney Island Fm, Comox Fm, Extension Fm, Protection Fm, De Courcy Fm, Geoffrey Fm, Gabriola Fm) * • Unnamed formations • Turtleback (East Sound)	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, gravelly silt, sandy silt, clayey sand, rubbley fines, lacustrine	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 • Haro Grp (Spieden Fm) • Decatur Grp (Constitution Fm) • Quaternary Grp (Vashon 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, morainal, organics, marine, undifferentiated, silty sand, gravelly sandy silt, clayey boulders, clayey mixed fragments	6
		Sand	Eolian, sand, bouldery organics, finey rubble, silty boulders, silty rubble, silty mixed fragments, silty gravel, silty sandy gravel	7

Table 5.3 (cont.) Aquifer medium and impact of the vadose zone rating table

Bedrock Formation	Bedrock Material	Mapped Surficial Aquifer Material	Terrain Map Material	*A* and *I* Rating
		Sand and gravel,	Colluvium, fluvial, glacio-fluvial, bouldery sand, gravelly sand, rubbley sand, bouldery rubbley sand, sandy boulders, sandy rubble, sandy gravel, sandy mixed fragments	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, gravelly mixed fragments, gravel, bouldery gravel, rubbley gravel, mixed fragments gravel, boulders, gravelly boulders, rubbley boulders, rubble, bouldery rubble, blocky rubble, blocks	9
				10

[yellow highlight] - values not encountered or rated in the pilot study

Figure 5.6 Aquifer medium parameter, rated according to Table 5.3



5.5 Soil Medium

The soil medium parameter completed during the pilot study was based on soil drainage, obtained from soil surveys in the National Soils Database (refer to table 4.1). However, as indicated by Liggett and Gilchrist (2010), digital versions of this data are only available for the southern half of Vancouver Island. To maintain data consistency across the entire phase 2 study area, an alternate source of data was used to determine soil media ratings. The first encountered texture value was obtained from the parsed terrain labels, and substituted for the soil drainage values used in the pilot study. Where texture values were not provided in terrain labels, the first encountered surficial material was used as the substitute for soil drainage values.

Because the ratings are based on soil media, a soil textural classification chart (Appendix 6, Newton, 2010) was used to associate terrain texture with soil medium. These values were rated according to the original U.S. EPA rating table (Table 5.4). The rated soil medium map is shown in Figure 5.7.

Gabriola Island was the only exception to this alternative soil rating method. Like the pilot study, soil ratings for Gabriola are based on soil drainage from the national soil surveys, as terrain mapping is not available. Further discussion of the methodology and soil drainage rating table is included in the pilot study report (Liggett and Gilchrist, 2010).

To ensure that texture or surficial material type from the terrain maps were appropriate values to substitute for soil drainage, the ratings obtained using each method were compared for the pilot study area of interest. 80% of ratings obtained in phase 2 were within two rating values of the pilot study, 90% percent were within three rating values, and only 1.8% had a difference of 7, 8, or 9 rating values. Review of these rating differences with high variability confirms that the discrepancies are due to polygon offsets between the soil dataset used in the pilot study and the terrain dataset used in phase 2.

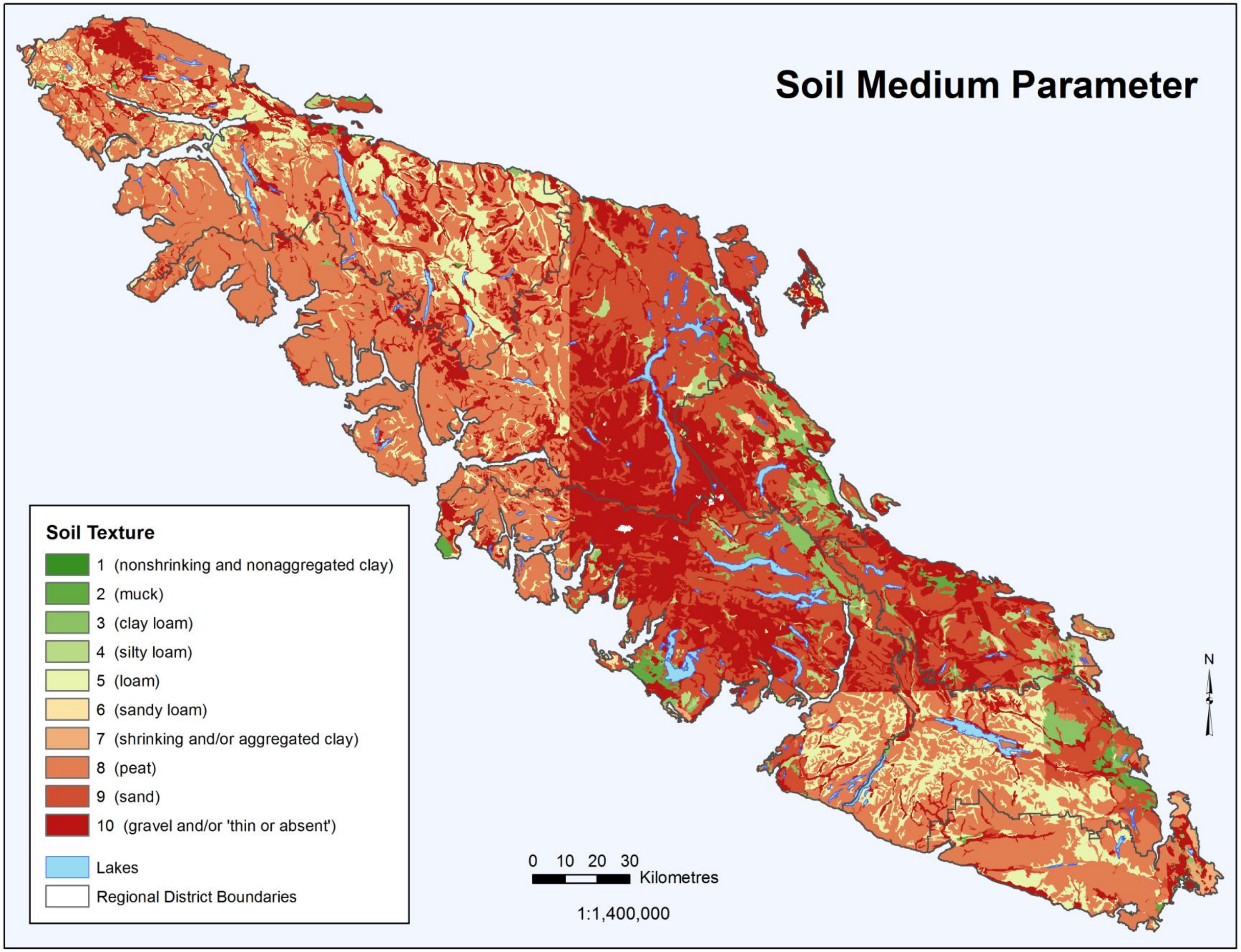
Further evaluation of the discrepancies also shows that there is no systematic error with the data. For example, marine material (W) makes up 48% of all the 7, 8, or 9 rating differences but only 18% of the *total* W values in the study area result in 7, 8, or 9 ratings differences. If there had been a systematic error with the data, approximately 50% of the total W values in the study area would have resulted in differences of 7, 8, or 9 between the pilot study and phase 2 ratings.

The comparison of ratings obtained using soil drainage (pilot study) and texture from the terrain maps indicates that the methodology used for phase 2 is acceptable. For further discussion concerning the compilation of the S parameter, along with the comparison between phase 2 and the pilot study, refer to Newton (2010).

Table 5.4 The soil rating table for all of Vancouver Island, containing the soil texture and ratings as defined in the DRASTIC manual (Aller et. al, 1987), and the associated substituted texture values from the terrain map.

Soil Texture	Substituted Texture Values	*S* Rating
Nonshrinking and Nonaggregated Clay	clay	1
Muck	Silty clay, sandy clay, mixed fragment clay, bouldery clay, fines, clayey fines, clayey silt, mud	2
Clay Loam	Lacustrine, silt, gravelly clay, gravelly silty clay	3
Silty Loam	Sandy silt, sandy fines, mixed fragment fines, humic mud	4
Loam	Alluvium, morainal, marine, bouldery silt, gravelly silt, gravelly sandy silt, rubbley fines, muddy boulders	5
Sandy Loam	Undifferentiated, silty sand, clayey sand	6
Shrinking and/or Aggregated Clay	Silty gravel, silty sandy gravel, silty mixed fragments, silty rubble, fine rubble, clayey boulders	7
Peat	Colluvium, Organics	8
Sand	Eolian, fluvial, glacio-fluvial, sand, bouldery organics	9
Gravel and/or 'Thin or Absent'	Bedrock, gravelly sand, rubbley sand, bouldery sand, bouldery rubbley sand, gravel, sandy gravel, mixed fragments gravel, rubbley gravel, bouldery gravel, mixed fragments, sandy mixed fragments, gravelly mixed fragments, sandy gravelly mixed fragments, rubble, sandy rubble, bouldery rubble, blocky rubble, boulders, sandy boulders, gravelly boulders, rubbley boulders, blocks	10

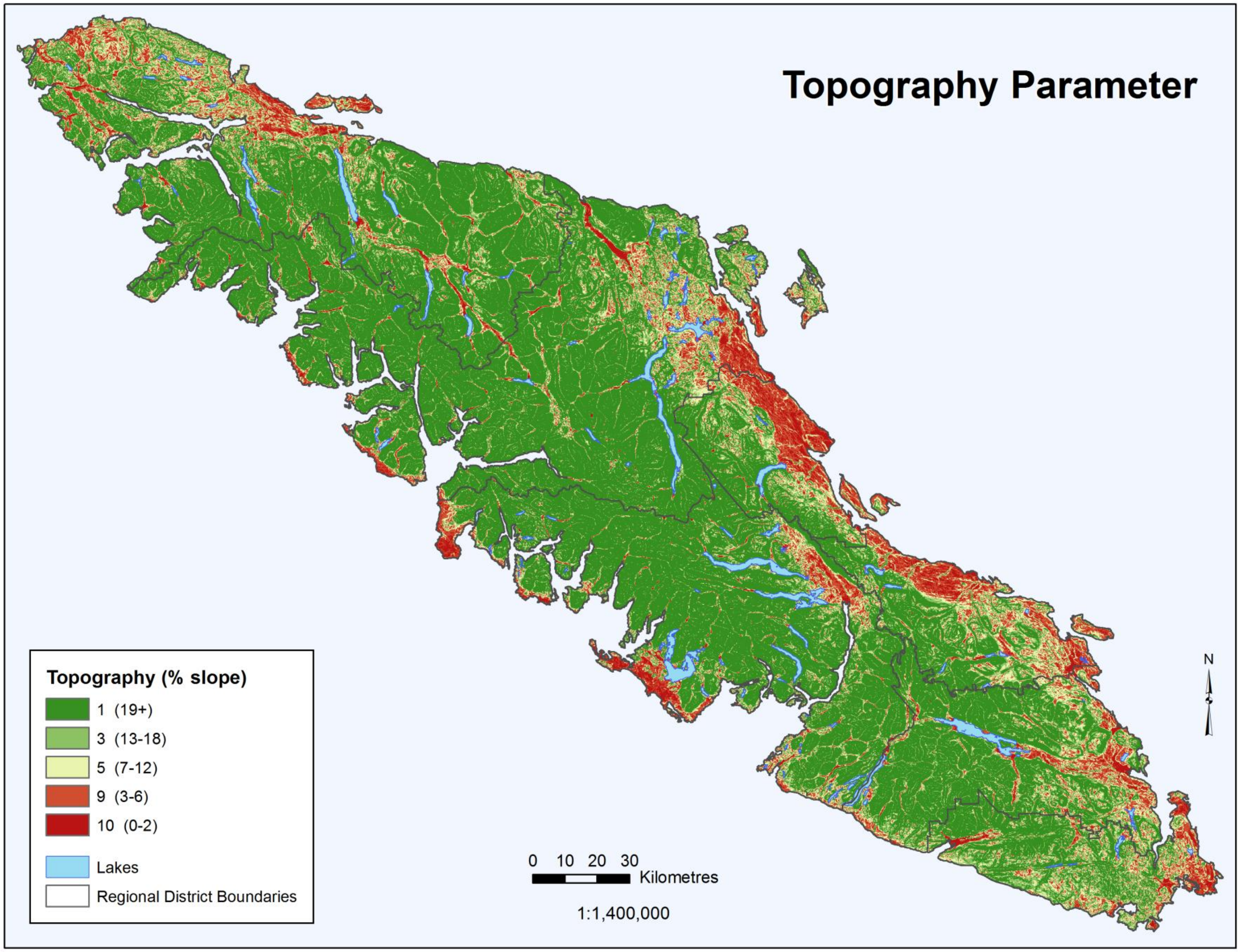
Figure 5.7 Soil medium parameter, rated according to Table 5.4



5.6 Topography

The topography parameter was completed using the same methodology and rating table as discussed in Liggett and Gilchrist (2010). Ratings of 1, 3, 5, 9, and 10 were also obtained for the phase 2 study area, as shown in Figure 5.8.

Figure 5.8 Topography parameter

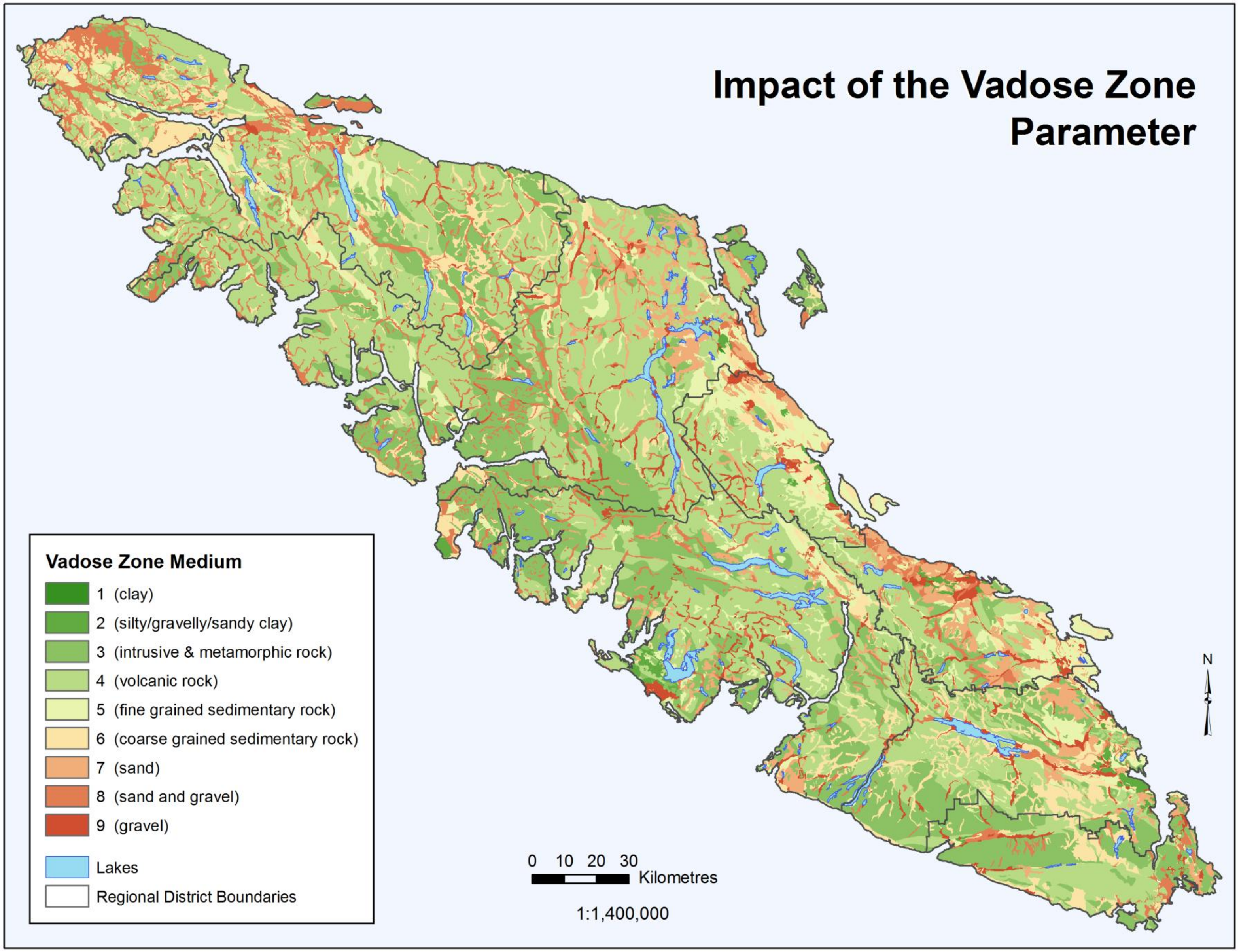


5.7 Impact of the Vadose Zone

As with the aquifer medium parameter, assembly of the I parameter followed a similar methodology to that defined in the pilot study (Liggett and Gilchrist, 2010). The most significant difference is for mapped surficial confined aquifers. As noted in Section 5.2, automated screening of the well records to determine confinement was not possible from the well lithology descriptions; hence it was assumed that all surficial aquifers were unconfined. This assumption is consistent with the other parameter ratings and is a conservative approach to assigning vulnerability ratings. The first encountered texture value from the lower stratigraphic layer of the terrain map was used to determine a rating for all surficial aquifers (mapped confined, mapped partially confined, mapped unconfined, and unmapped). Bedrock aquifers were rated using the same methodology discussed in the pilot study.

Like the pilot study, the more comprehensive rating table produced for the A parameter (Table 5.3) was also used to provide I ratings for the surficial material and bedrock geology values identified in phase 2. The rated impact of the vadose zone map is shown in Figure 5.9.

Figure 5.9 Impact of the vadose zone parameter, rated according to Table 5.3



5.8 Conductivity

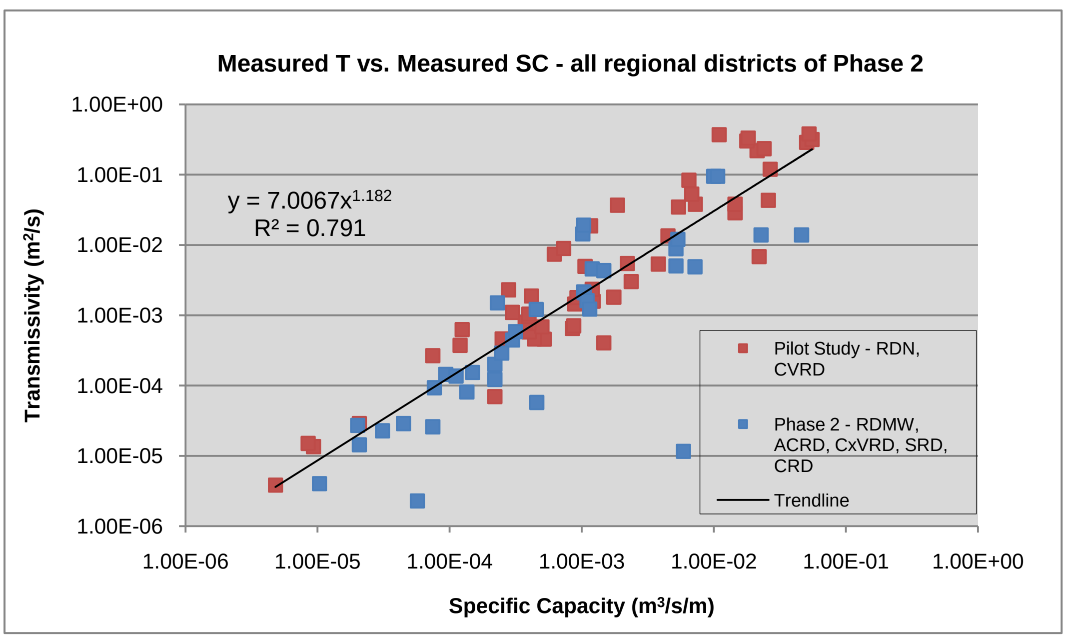
Hydraulic conductivity ratings were determined using the same methodology discussed in the pilot study (Liggett and Gilchrist, 2010). The pilot study collected data on 92 wells from 71 reports for the RDN and CVRD; phase 2 collected data on 143 wells from 72 reports completed for sites in the five additional regional districts. While hydraulic conductivity (K) was only reported for one well in the pilot study, 49 wells in phase 2 had reported K values. An additional 55 wells contained transmissivity (T) values, and 39 wells contained only specific capacity (SC) values.

As discussed in Liggett and Gilchrist (2010), K can be calculated by dividing T by the effective aquifer thickness. For wells containing SC values only, the relationship between reported SC and T values can be used to estimate T. Fifty-three pairs of SC and T values were used to determine this relationship for the RDN and CVRD in the pilot study. An additional 37 pairs of SC and T values were extracted from reports for the remaining Vancouver Island regional districts. As a result, the relationship between T and SC was re-calculated for the phase 2 analysis to include all pairs of reported SC and T values (Figure 5.10). The relationship between SC and T is given in Equation 5.1:

$$T = 7.006\ SC^{1.182} \qquad (5.1)$$

Equation 5.1 incorporates data obtained from both the pilot study and the phase 2 analyses. As a result, it was used to determine T for all wells containing only SC values. In addition to the 39 wells from the phase 2 analysis, the 21 wells from the pilot study were also updated to reflect the revised relationship.

Figure 5.10 Relationship between transmissivity and specific capacity for wells in all regional districts.



The reported T values (126 wells for the pilot study and phase 2 combined) and calculated T values (60 wells for the pilot study and phase 2 combined) were used to calculate K by dividing T by the effective aquifer thickness. For unconsolidated aquifers, this was represented by the screen length. For bedrock aquifers, effective aquifer thickness was represented by 5% of the open-hole interval (Liggett and Gilchrist, 2010). When combined with the reported K values (50 from both the pilot study and phase 2 combined), hydraulic conductivity was calculated for 155 wells in 40 aquifers in the phase 2 study area (Table 5.5). Screen length was not reported for 43 wells (although 11 did have K values), and 54 wells were in unidentified aquifers (5 of which did not have screen length).

Table 5.5 Geometric mean of transmissivity and hydraulic conductivity for aquifers in the phase 2 study area. Aquifers from the pilot study are included, as values were updated in the phase 2 analysis. The C rating is based on the original table in Aller et al. (1987), as shown in Table 5.7. Some of the aquifers below are not the upper-most aquifer but were completed in the same formation as the upper-most aquifer.

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	3.58E-05	1.35E-05	1.17E+00	2	**1**
204	Bedrock	Island Intrusions	1.42E-05	1.98E-06	1.71E-01	2	**1**
207	Bedrock	Bonanza Grp and Island Intrusions	1.73E-04	3.50E-05	3.03E+00	1	**1**
218	Bedrock	Benson Fm (Nanaimo Grp)	6.03E-05	2.14E-05	1.85E+00	1	**1**
606	Bedrock	Metchosin Igneous	9.17E-07	1.52E-07	1.32E-02	11	**1**
607	Bedrock	Nanaimo Group	8.37E-06	2.09E-06	1.81E-01	2	**1**
608	Bedrock	Island Plutonic Suite	1.85E-05	3.58E-06	3.09E-01	8	**1**
680	Bedrock	Wark-Colquitz Complex	3.81E-05	2.19E-06	1.90E-01	43	**1**
739	Bedrock	Cenozoic, Quaternary glacial and post glacial deposits	2.59E-05	2.40E-05	2.08E+00	1	**1**
740	Bedrock	Mesozoic, Upper Cretaceous De Courcy Formation	6.25E-05	2.05E-05	1.77E+00	1	**1**
900	Confined	glaciofluvial deposits	1.53E-04	3.35E-05	2.90E+00	1	**1**
159	Unconfined	sands and gravels (unknown)	6.97E-04	6.82E-05	5.89E+00	2	**2**
215	Confined	Quadra	1.02E-03	2.53E-04	2.18E+01	4	**4**

216	Confined	Quadra	1.12E-03	3.26E-04	2.81E+01	3	**4**
219	Confined	Quadra	7.21E-04	2.65E-04	2.29E+01	8	**4**
408	Confined	Quadra Sediments	1.74E-03	3.14E-04	2.71E+01	3	**4**
217	Unconfined	Quadra	8.80E-04	3.64E-04	3.14E+01	12	**6**
205	Confined	Vashon	2.22E-03	8.21E-04	7.09E+01	1	**8**
410	Unconfined	Salish Sediments	3.36E-03	5.79E-04	5.00E+01	1	**8**
415	Unconfined	Salish Sediments	1.20E-03	7.98E-04	6.90E+01	1	**8**
611	Confined	Quadra Sediments; Cowichan Head Form.	1.21E-03	7.93E-04	6.85E+01	1	**8**
685	Unconfined	Capilano & Salish Sediments	1.50E-03	7.41E-04	6.41E+01	2	**8**
161	Confined	Capilano	2.40E-01	4.99E-02	4.31E+03	1	**10**
163	Unconfined	Quadra	5.28E-02	1.40E-02	1.21E+03	1	**10**
172	Semi-Confined	Salish	1.44E-01	4.60E-02	3.97E+03	8	**10**
186	Unconfined	Salish	1.14E-01	2.08E-02	1.80E+03	6	**10**
187/188	Semi-Confined	Vashon/Salish	4.02E-02	1.41E-02	1.22E+03	7	**10**
188	Semi-Confined	Vashon	5.29E-02	2.27E-02	1.96E+03	2	**10**
189	Unconfined	Salish	1.34E-02	4.48E-03	3.87E+02	1	**10**
190	Confined	Salish	5.77E-03	2.52E-03	2.18E+02	4	**10**
197	Confined	Vashon	1.26E-03	1.29E-03	1.11E+02	3	**10**
221	Unconfined	Salish	1.26E-02	3.16E-03	2.73E+02	1	**10**
412	Unconfined	Salish Sediments	7.66E-03	3.87E-03	3.34E+02	1	**10**
414	Unconfined	Salish Sediments	1.48E-02	1.55E-03	1.34E+02	2	**10**
416	Unconfined	Quadra	1.87E-02	3.06E-03	2.65E+02	1	**10**
419	Unconfined	Quadra Sediments	3.30E-02	1.40E-03	1.21E+02	2	**10**
599	Unconfined	Capilano Sediments & Vashon Till	2.37E-03	2.59E-03	2.24E+02	1	**10**

610	Unconfined	Quadra Sediments	3.31E-03	1.36E-03	1.17E+02	1	**10**
612	Unconfined	Quadra Sediments; Cowichan Head Form.	1.44E-02	3.93E-03	3.40E+02	1	**10**
858	Unconfined	glaciofluvial deposits	1.92E-02	1.55E-03	1.34E+02	1	**10**

As with the pilot study, mapped surficial aquifers were rated using the geometric mean of hydraulic conductivity from all wells mapped in the same geologic formation (Table 5.6), and the original rating table in Aller et. al (1987). The geological formation ratings are identical to those obtained during the pilot study with the exception of the combined Capilano & Salish formation reported for one aquifer. Calculated conductivity values from two wells in this aquifer assign a vulnerability rating of 8 to the combined Capilano and Salish formations. As additional hydrogeological reports become available, these values may change.

Table 5.6 Geometric mean of hydraulic conductivity and rating for mapped aquifer formations – phase 2 and pilot study data combined.

Formation (from aquifer worksheets)	T (m^2/s)	K (m/s)	K (m/d)	Number of wells	C Rating
Bedrock	1.77E-05	1.85E-06	1.60E-01	72	**1**
Glaciofluvial Deposits	1.71E-03	2.28E-04	1.97E+01	2	**4**
Quadra	1.49E-03	4.54E-04	3.92E+01	37	**6**
Capilano & Salish	1.50E-03	7.41E-04	6.41E+01	2	**8**
Capilano	2.40E-01	4.99E-02	4.31E+03	1	**10**
Capilano & Vashon	2.37E-03	2.59E-03	2.24E+02	1	**10**
Salish	3.13E-02	9.64E-03	8.33E+02	25	**10**
Vashon	2.49E-03	3.11E-03	2.69E+02	6	**10**
Vashon & Salish	4.02E-02	1.41E-02	1.22E+03	6	**10**

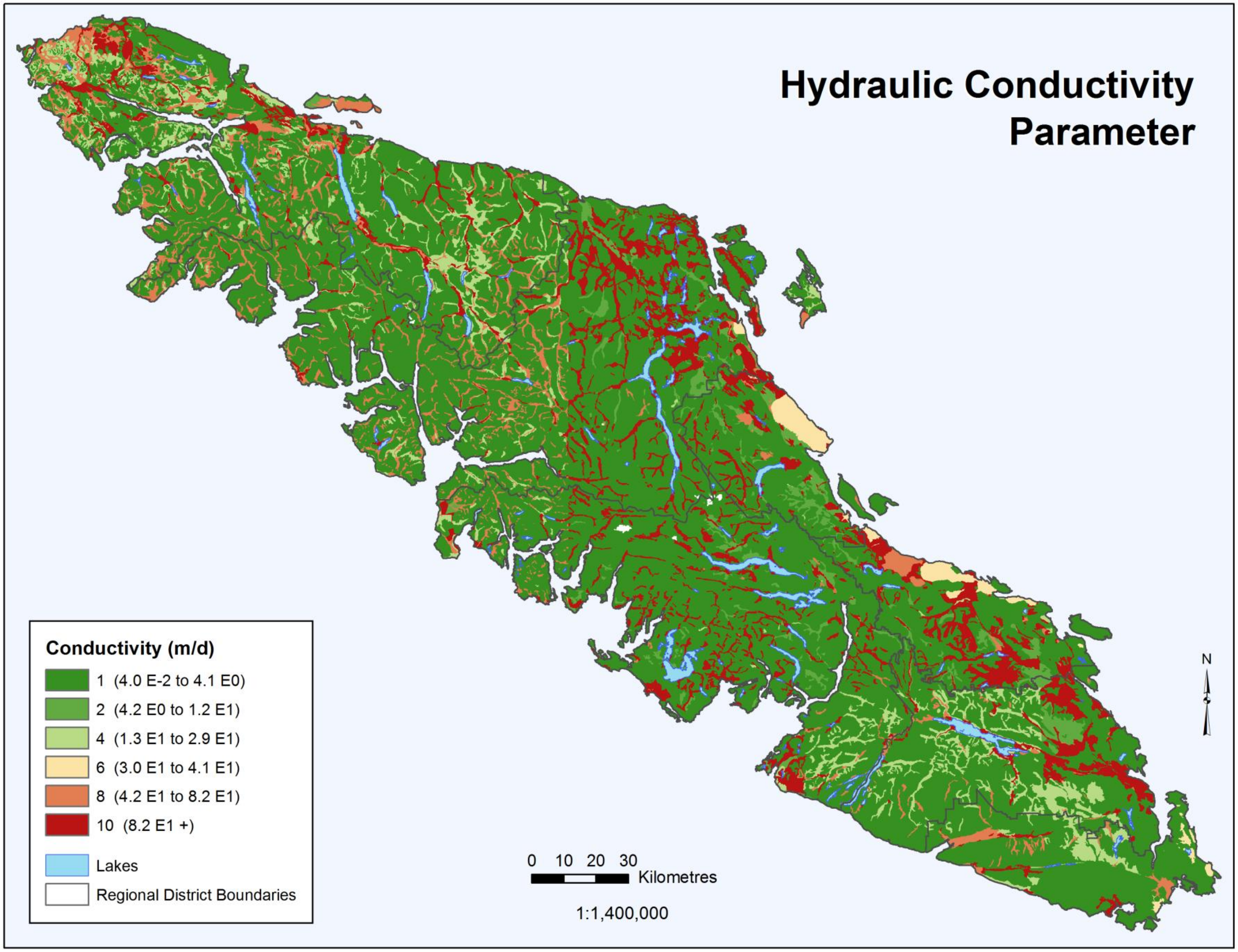
As with the A and I parameters, a more comprehensive rating table (Table 5.7) has been developed for phase 2. The pilot study rating table was expanded to include the full range of aquifer formations and texture values encountered in the phase 2 study area. The overall conductivity ratings for aquifer formations are based on the results of combining the data obtained by the pilot study and phase 2. The rated hydraulic conductivity map is shown in Figure 5.11.

Table 5.7 Hydraulic conductivity rating table for all encountered materials on Vancouver Island. (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
$4.0x10^{-2} – 4.1x10^{0}$	Bedrock – all types (B), clay (T), silty clay (T), gravelly silty clay (T), sandy clay (T), clayey silt (T), fines (T), mud (T), Bedrock (T)	1
$4.2x10^{0} – 1.2x10^{1}$	Silt (T), sandy silt (T), clayey mixed fragments (T), sandy fines (T), gravelly clay (T), Lacustrine (T)	2
$1.3x10^{1} – 2.9x10^{1}$	Morainal (T), Marine (T), silty mixed fragments (T), bouldery silt (T), gravelly silt(T), gravelly sandy silt (T), rubbley fines (T)	4
$3.0x10^{1} – 4.1x10^{1}$	Quadra Sand (W), Quadra Sediment (W), clayey sand (T), clayey boulders (T)	6
$4.2x10^{1} – 8.2x10^{1}$	Capilano & Salish combined (W), Glacio-Fluvial (W) & (T), Terraced Fluvial (W), Pleistocene and Holocene deposits(W), Fraser Formation (W), Fraser Glaciation (W), Alluvial Fan (W), Cenozoic, Quaternary glacial and post glacial (W), Alluvium (T), Organics (T), Undifferentiated (T), silty sand (T), Colluvium (T), Fluvial (T), mixed fragments (T), gravelly mixed fragments (T), silty boulders (T), silty gravel (T), silty rubble (T), silty sandy gravel (T), bouldery organics (T)	8
$>8.2x10^{1}$	Capilano Sediments (W), Vashon Drift (W), Vashon Till (W), Salish Sediments (W), unknown sands and gravels (W), Eolian (T), sand (T), gravelly sand (T), bouldery sand (T), rubbley sand (T), bouldery rubbley sand (T), gravel (T), sandy gravel (T), rubbley gravel (T), bouldery gravel (T), mixed fragments gravel (T), sandy mixed fragments (T), rubble (T), sandy rubble (T), finey rubble (T), gravelly rubble (T), bouldery rubble (T), blocky rubble (T), boulders (T), sandy boulders (T), gravelly boulders (T), rubbley boulders (T), blocks (T)	10

____________ - values not encountered or rated in the pilot study

Figure 5.11 Hydraulic conductivity parameter, rated according to Table 5.7



5.9 DRASTIC Calculation

All seven rated DRASTIC parameters were combined using the weighted sum equation determined by the U.S. EPA, and a 100 m grid cell size.

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

Unlike the pilot study, the intrinsic vulnerability of the upper-most surficial aquifers were derived assuming that they are all unconfined. Confinement is discussed in greater detail in Section 5.2.

6.0 RESULTS

Results of the phase 2 intrinsic vulnerability mapping were compared to those obtained by the pilot study. The mapping extent of the phase 2 analysis was also limited by the availability of well data and the extent of the final depth to water parameter. But, rather than using the 250 m asl contour as a boundary for the analysis, the depth to water parameter was limited to within 5 km of wells used in the interpolation.

Unlike the pilot study, the phase 2 mapping was completed given the assumption that all upper-most surficial aquifers were unconfined (Section 5.2). This is a more conservative approach to determining vulnerability, often resulting in higher ratings. A comparison with the classified pilot study vulnerability ratings (into three categories) was completed to assess the differences in the final intrinsic vulnerability between the two phases of the project.

Despite the differences in methodology between the pilot and phase 2 studies, the intrinsic vulnerability map completed in phase 2 (Figure 6.1) results in the same range of vulnerability: a low of 59, and a high of 218. Figure 6.2 illustrates the final vulnerability map classified into high, moderate, and low vulnerability using the breakpoints discussed in Liggett and Gilchrist (2010). Figure 6.3 compares the classified results of phase 2 with those of the pilot study.

Across the entire pilot study area of interest, 74.9% of the total grid cells were assigned the same vulnerability class by both the phase 2 analysis and the pilot study. 15.2% of the total grid cells were rated one class higher and 9.5% were rated one class lower than the pilot study. 0.3% of the total grid cells were rated two classes higher and 0.1% were rated two classes lower than the pilot study.

A similar review was completed for mapped confined aquifers only, and it was found that 62.3% of all grid cells within confined aquifers were assigned the same class as the pilot study, 36.1% were one class higher than the pilot study, and 0.2% were two classes higher than the pilot study. Only 1.4% of grid cells had a lower class than the pilot study. These results suggest that if an aquifer is believed to be confined, the final vulnerability could decrease by one class (i.e. from high to moderate or moderate to low). As noted by Liggett and Gilchrist (2010), the classification of intrinsic vulnerability values into categories does not reflect gradational changes between areas, which may affect this comparison. If the breakpoints used to classify the map were altered, the results obtained by this comparison would change.

A visual comparison between the final classified vulnerability map obtained by the phase 2 study and the pilot study was also completed. In addition to the differences already noted within confined aquifers, differences in class also occur where the upper-most aquifers are delineated based on the overburden thickness rather than terrain. This is to be expected, due to the number of additional wells available for the phase 2 analysis.

In addition to confinement, other sources of variation in the results between the pilot study and phase 2 methodologies include the number of additional wells used to complete the D parameter, and the use of lower stratigraphic data from the terrain map for the A, I, and C parameters. Furthermore, the use of the terrain map in place of soil surveys for the S parameter has also contributed to the differences in the results shown on the final vulnerability maps.

Figure 6.1 Intrinsic aquifer vulnerability map for the phase 2 study area

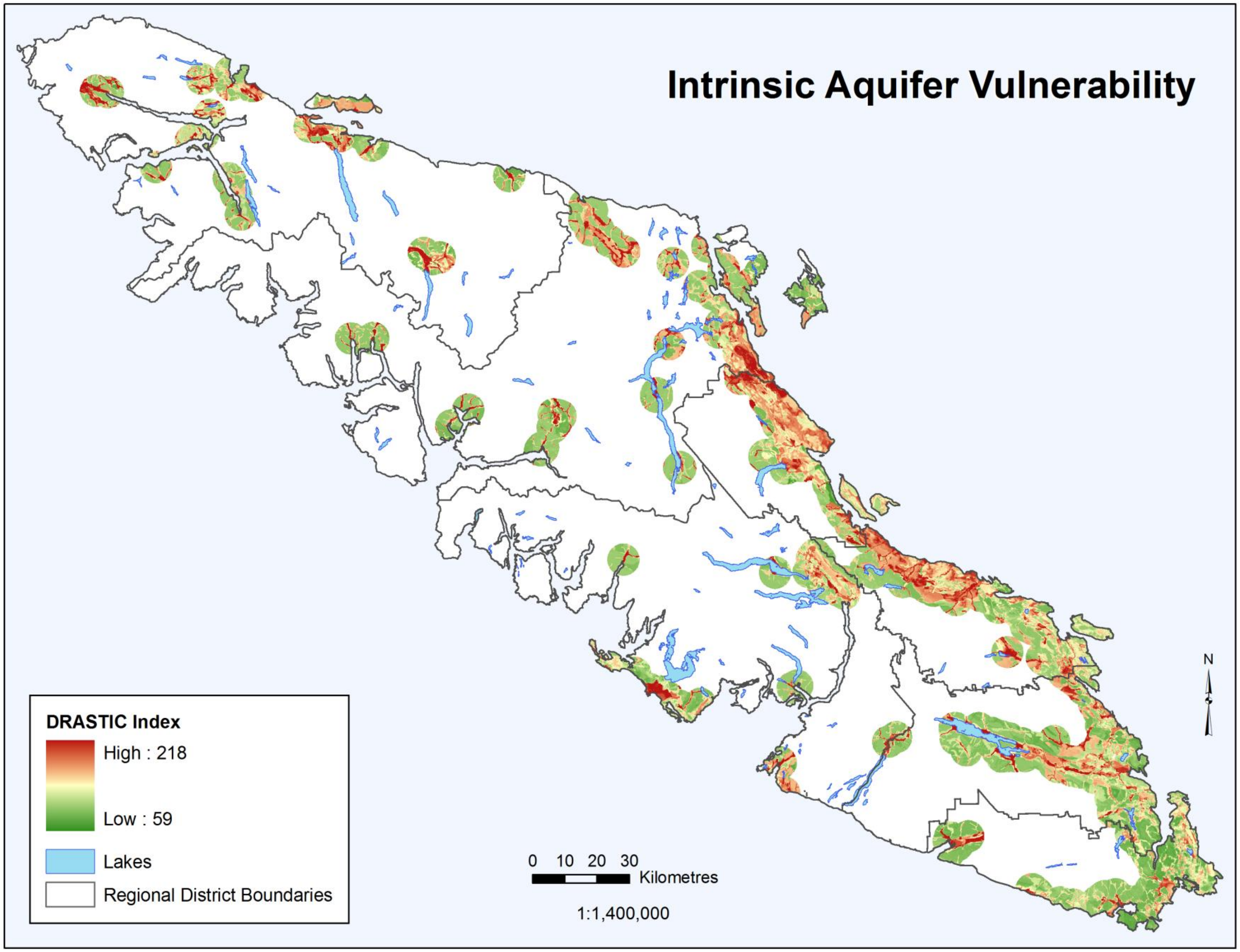


Figure 6.2 Intrinsic aquifer vulnerability map for the phase 2 study area, grouped into three classes

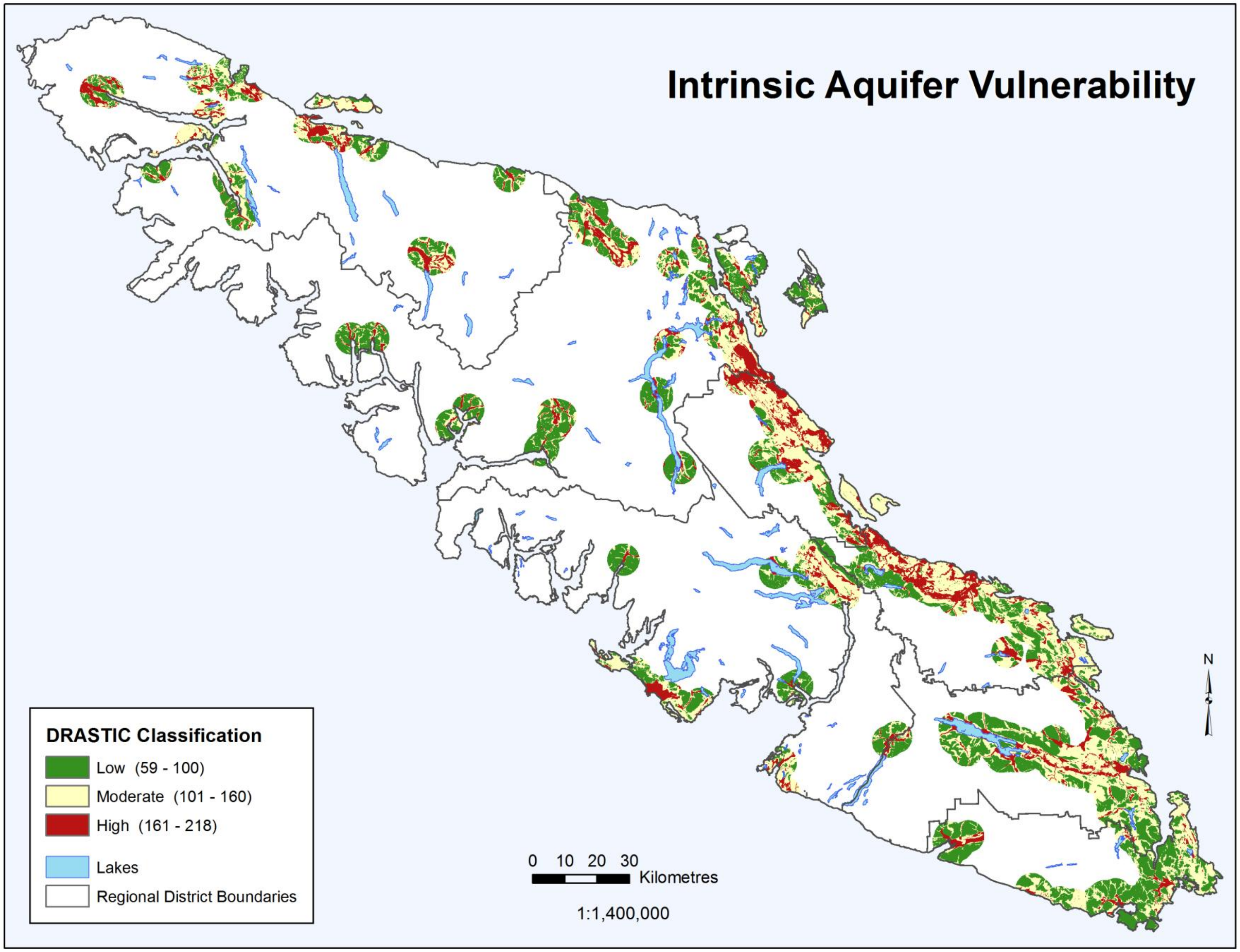
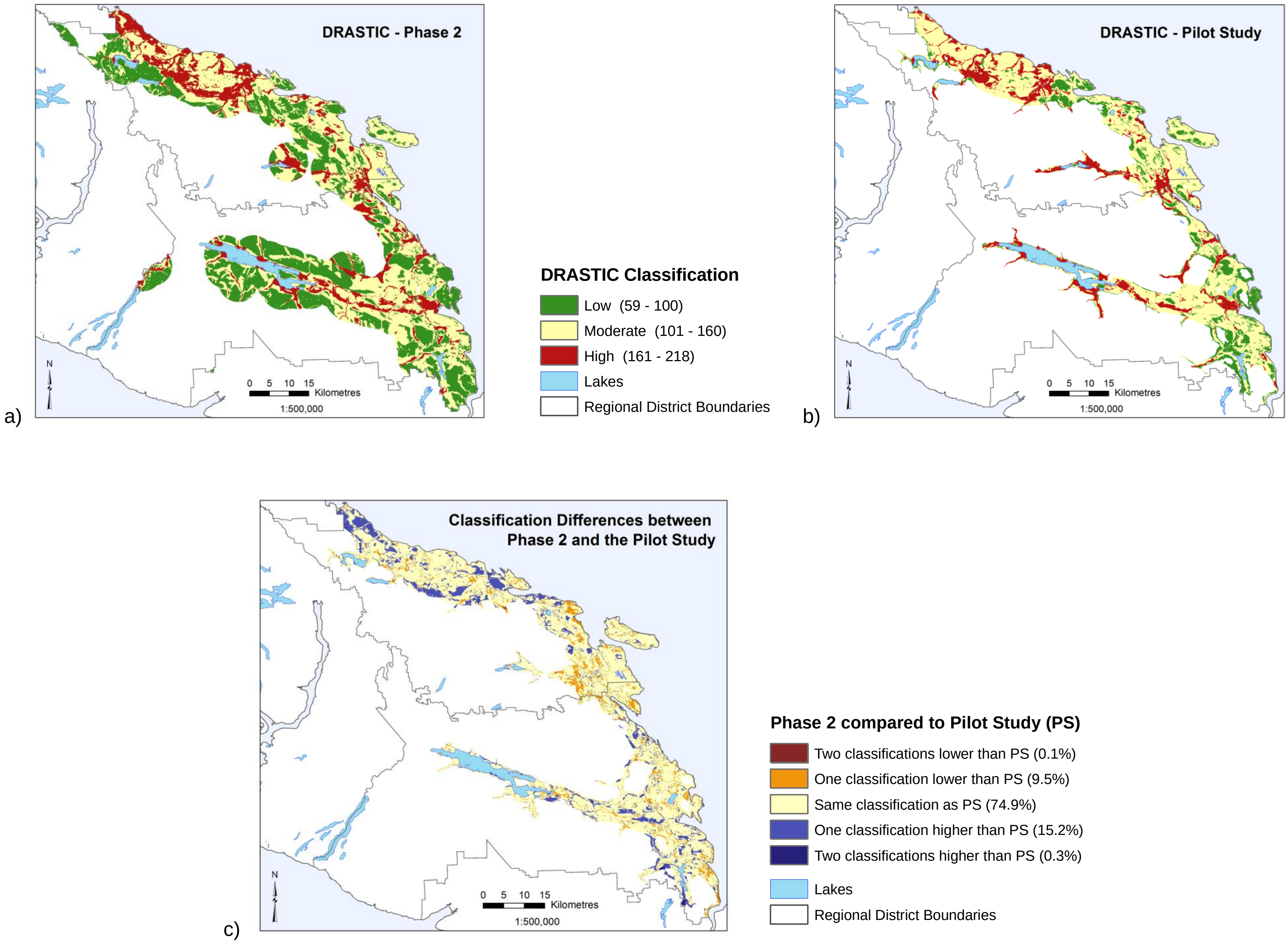


Figure 6.3 DRASTIC intrinsic vulnerability from a) the phase 2 study, b) the pilot study, and c) the difference between both studies



6.1 Assumptions and Limitations

Phase 2 of the VMP was completed using similar datasets and methods as in the pilot study. Therefore, many of the assumptions and limitations discussed in Liggett and Gilchrist (2010) apply to the phase 2 intrinsic vulnerability analysis. The following section discusses only the limitations and assumptions that differ from those of the pilot study.

Compilation of Terrain Map

The terrain map was used to assemble the upper-most aquifer map, along with the A, S, I, and C parameters. Despite the preparation of this dataset for use in the analysis, inconsistencies may still exist. As documented in Newton (2010), it is assumed that the original labeling of the terrain polygons is correct, and that the labels were accurately converted to digital format. It should also be noted that labeling of the polygons is subjective, which may explain why many polygons lacked texture information or were unlabelled.

Aquifer Delineation

The upper-most aquifer map is a compilation of three datasets. Aquifers mapped by the BC Aquifer Classification system are assumed to be of the highest quality. Aquifers classified using the interpolated overburden thickness are considered to be of the second highest quality, as these are based on confirmed well data. Aquifers classified using the terrain maps are considered to be of the lowest quality since this dataset offers limited information with regard to overburden thickness.

The critical overburden thickness was determined to be 10.45 m (Section 5.1). However, the terrain map only distinguishes between veneer (< 1 m) and blanket (> 1 m) overburden thickness. As a result, the extent of surficial aquifers may be overestimated where the terrain map was used.

Because this study represents aquifer vulnerability on a regional scale, many specific aquifer types, including karst aquifers, are not identified in the upper-most aquifer map. Modelling studies indicate that the DRASTIC method is not as accurate as some other vulnerability mapping methods for karst aquifers (Neukum et. al., 2008). Therefore, the results of this study should be treated with caution where karst aquifers exist, and further work should be done to confirm the results. However, on Vancouver Island, karst aquifers only represent 2.4% of the area mapped by this study, and many of them are in remote locations.

Depth to Water

Further to the limitations discussed in Liggett and Gilchrist (2010), it was assumed that the upper-most aquifers of Vancouver Island are unconfined (Section 5.2). Confining layers lower an aquifer's intrinsic vulnerability as contaminant flow into the aquifer from above is reduced. Consequently, the assumption that all aquifers are unconfined has resulted in generally higher vulnerability ratings than obtained by the pilot study where confined aquifers have been mapped.

Soil Medium

The soil medium parameter reflects the difference in standards used to complete the original terrain mapping. Visible in Figure 5.7, two distinct boundaries delineate areas of higher and lower vulnerability ratings. The area with higher ratings includes specific texture values in the terrain polygon labels, allowing vulnerability ratings to be more accurately assigned. The majority of ratings in the two areas displaying lower vulnerabilities are based on surficial material values. Because these values represent a range of textures, the vulnerability ratings were assigned based on an “average” texture, which resulted in lower vulnerability ratings. Identification of alternative sources for soil information could potentially refine this parameter; however, this task was beyond the scope of this study.

Impact of the Vadose Zone

As with the depth to water parameter, the assumption that aquifers are unconfined has resulted in a more conservative approach to assigning vulnerability ratings. Previously, all identified surficial confined aquifers were assigned the lowest vulnerability rating of 1. In the current analysis, all surficial confined aquifers are assigned vulnerability ratings based on the first encountered texture of the lower stratigraphic layer of the terrain map. This has resulted in intrinsic vulnerability ratings from 1 to 9 where aquifers would have previously been rated as 1 by the pilot study.

Of the 164 mapped aquifers in the phase 2 study area, 46 are classified as surficial confined. This aquifer type represents just 18% of the total area of all mapped aquifers, and only 5% of the total aquifers included in the final intrinsic vulnerability map (Figure 6.1). Where mapped confined aquifers do occur, the DRASTIC vulnerability is generally higher than would have been predicted by the pilot study methodology.

DRASTIC Intrinsic Vulnerability Map

As with the pilot study, the above noted assumptions and limitations contribute to the uncertainty in the final vulnerability map. To reiterate Liggett and Gilchrist (2010), the final intrinsic vulnerability map is meant to be a regional screening tool only; it is not meant to represent or replace site specific investigation. This study represents an aquifer’s vulnerability to contamination based on its natural characteristics. Land-use activities and their potential hazards must also be considered when assessing the potential risk of contamination.

7.0 CONCLUSIONS AND FUTURE WORK

Intrinsic aquifer vulnerability mapping was completed for all regional districts of Vancouver Island, as well as Gulf Islands not previously mapped by other studies. Using the DRASTIC indexing method developed by the U.S. EPA, seven parameters – depth to water, recharge, aquifer medium, soil medium, topography, impact of the vadose zone, and hydraulic conductivity – were mapped, rated, and combined to show the regional distribution of intrinsic vulnerability.

The mapping completed during phase 2 of the VMP provides the best estimate of intrinsic aquifer vulnerability, given the resources available to complete the analysis. It provides a basis for making land-use decisions that account for regional aquifer vulnerability. However, in many instances, more detailed hydrogeological studies will be required to better characterize and confirm the results of this study. This is particularly relevant for areas where high vulnerability ratings have been assigned that could limit potential land-use.

8.0 REFERENCES

Aller, L., Bennett, T., Lehr, J., Petty, R. and Hackett, G., 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. EPA-600/2-87-035, National Water Well Association, Dublin, Ohio / EPA Ada. Oklahoma. 641 pp.

Berardinucci, J. and Ronneseth, K., 2002. Guide to using the BC aquifer classification maps for the protection and management of groundwater resources, Ministry of Water, Land, and Air Protection, Victoria, BC. 54 pp.

Denny, S.C., Allen, D.M. and Journeay, J.M., 2007. DRASTIC-Fm: A Modified Vulnerability Mapping Method for Structurally-Controlled Aquifers. Hydrogeology Journal, 15(3): 483-494.

Howes, D.E. and Kenk, E., 1997. Terrain Classification System for BC, version 2. Fisheries Branch, Ministry of Environment and Surveys and Resource Mapping Branch, Ministry of Crown Lands Province of British Columbia. MOE Manual 10, (Version 2). 111 pp.

Liggett, J. and Gilchrist, A., 2010. Technical Summary of Intrinsic Vulnerability Mapping Methods in the Regional Districts of Nanaimo and Cowichan Valley. Geological Survey of Canada, Open File 6168. 64 pp.

Ministry of Energy and Mines, Forest Renewal BC. Digital Terrain Map Library Projects – Projects (Converted Maps). Accessed January 2009. http://webmap.em.gov.bc.ca/mapplace/maps/frbc/projects.mwf

Ministry of Energy and Mines, Forest Renewal BC. Digital Terrain Map Library Projects – Raster Terrain Download. Accessed January 2009. http://webmap.em.gov.bc.ca/mapplace/maps/frbc/projects.mwf

Ministry of Environment, Ecosystem Information Section, Ecosystem Branch, 2007. Standard for Digital Terrain Data Capture in British Columbia; Terrain Technical Standard and Database Manual Errata 2006-1.1 to accompany Version 1 (1998 RIC). 49 pp.

Neukum, C., Hötzl, H. and Himmelsbach,T., 2008. Validation of Vulnerability Mapping Methods by Field Investigations and Numerical Modeling. Hydrogeology Journal, 16(4): 641-658.

Newton, P., 2010. Data Preparation and Automation for DRASTIC Vulnerability Mapping of Vancouver Island: Terrain Map, Aquifer Delineation and Assembly of A, S, I and C Parameters. Vancouver Island University, Nanaimo. BC. 47 pp.