Comparison of DRASTIC and DRASTIC-Fm methodologies for evaluation of intrinsic susceptibility of coastal bedrock aquifers and the adjustment of DRASTIC-Fm Fractured Media parameter

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Overview

Regional mapping of the intrinsic susceptibility of aquifers (commonly referred to as aquifer vulnerability mapping) to surface contaminants provides a tool to supply decision makers and water resource managers with quantifiable and visual representations of risk to aquifers. With increased development pressure along the coast of Vancouver Island and of specific interest to this study, the southern Gulf Islands, it has become increasingly important to quantify, analyze and classify risk to aquifers as many residents use groundwater as a main source of drinking water (Denny et al., 2007).

The DRASTIC methodology, originally developed by the US Environmental Protection Agency, utilizes seven parameters of groundwater physical characteristics that impact groundwater pollution potential. Making up the 'DRASTIC' acronym, these parameters include: Depth to Water (D), Net Recharge (R), Aquifer Media (A), Soil Media (S), Topography (T), Impact of the Vadose Zone (I) and Hydraulic Conductivity (C) of the aquifer. The DRASTIC method has been applied to regional study areas in BC including areas of Vancouver Island and the southern Gulf Islands where sufficient well data are available to meet parameter inputs.

A modification to the original DRASTIC methodology titled DRASTIC-Fm (Denny et al., 2007) incorporates the structural characteristics of fractured bedrock aquifers as an additional influencing parameter. This modified method was applied to a local study of the southern Gulf Islands where structural bedrock is an important element to the hydrogeological characteristics of the islands (Denny et al., 2007). This revision to the methodology produced an overall possible range of intrinsic susceptibility values inconsistent with other DRASTIC studies; DRASTIC employs a 23-230 range, and DRASTIC-Fm employs a 26-260 range.

In 2010 a DRASTIC study carried out on Vancouver Island created an area of DRASTIC evaluation overlap with the results of the 2007 study on Gabriola Island. This project compares the results of the two DRASTIC methods used for the study area and utilizes sensitivity analysis techniques to identify the variation of input parameters between the two studies. Parameter evaluation results are then used guide the incorporation of Fm characteristics into the C parameter to re-generate a new intrinsic aquifer susceptibility map that has the same overall range as the rest of the province that was assessed with the original DRASTIC methodology.

This document is formatted to represent the consecutive flow of the project phases. Part 1 of this report outlines the methodology and results of comparing the differences in parameter ratings between the two studies. Of particular interest, the study area for Part 1 of this project is the area of overlap between the two studies occurring on Gabriola Island. Part 2 of this report describes the techniques used to reweight the results of the DRASTIC-Fm study to incorporate the Fm rated values into the C parameter rated values and the resulting updated intrinsic susceptibility values for the southern Gulf Islands.

Acknowledgements

This project could not have been completed without the expert input and contribution from its project partners; special thanks to Diana Allen (Simon Fraser University), Alan Gilchrist (Vancouver Island University), Pamela Newton (Regional District of Nanaimo), Sylvia Barroso, Pat Lapcevic, and Scott Allen (Ministry of Forests Lands and Natural Resource Operations). Thank you to the Vancouver Island University Advanced Diploma in GIS Applications faculty including Dave Cake and Brad Maguire for their support. A special thank you to the Ministry of Forests, Lands and Natural Resource Operations, West Coast Regional Office staff for the welcoming atmosphere, and to the Regional District of Nanaimo for their support.

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PART 1.0 Comparison of DRASTIC and DRASTIC-Fm methodologies for evaluation of intrinsic susceptibility of coastal bedrock aquifers

1.1 Introduction

The addition of the Fractured Media parameter to the DRASTIC-Fm study produced an overall intrinsic susceptibility range that differs from the Vancouver Island study completed in 2010. Of particular interest, the study area for Part 1 of this project is the difference of results in areas of overlap on Gabriola Island. The purpose of this part of the report is to summarize the methodology and results of comparing the differences between the DRASTIC and DRASTIC-Fm parameters as rated rasters from 1-10. Identifying areas of high variability between the rated rasters applied to each of these two studies may aid in highlighting where the methodology used for each study differs the greatest. This information was utilized to outline the next steps in the broader project goal which aims to incorporate the Fm parameter into one of the original seven DRASTIC parameters.

For the purposes of this part of the report, 'VI' will refer to the Vancouver Island DRASTIC study carried out in 2010, and 'Fm' will refer to the DRASTIC-Fm study carried out in 2007 on the southern Gulf Islands.

1.2 Methodology

Datasets, including the rated raster files used in each of the VI and Fm studies, were acquired from project authors respectively. Covering a larger regional area, the VI grid cell size was 100m x 100m, whereas the Fm study, carried out on a local scale, had a grid cell size of 5m x 5m. To aid in geoprocessing efficiency, all original rated raster files were clipped to Gabriola Island as well as re-projected to NAD83 Albers. The 5m x 5m grid sized Fm rated rasters were resampled and aligned with the 100m x 100m VI rated rasters for each parameter respectively. The final adjusted Fm 100 m pixel rasters were then subtracted from the VI 100 m original rated raster for each parameter and the resulting difference saved as absolute values. Local detail of the Fm rasters were lost upon resampling to such a larger grid size of 100 m, but it is still feasible for the purposes of this step to visualize areas where the differences between studies are greatest.

Part 1 Result figures display 3 maps per parameter; one of each of the original rated raster used in both studies and a third map showing the difference between these two original rated rasters. The same colour ramp was used for comparing the original rated raster maps to each other, and a different color ramp was applied to the final difference maps. The final difference maps were classified into sets of two starting with 0 or no change, 1-2 showing little difference, and 9-10 showing greater difference. See Figure 1 for the classification color scheme used as described. As each parameter affects the susceptibility of an aquifer to varying degrees, it was determined best not to label these high, moderate, and low degrees of difference, but just to show the values of the differences.

The Results section below displays the total pixel count of the difference value between parameters. These values may help give a better sense of where the values of greatest difference occur per parameter.

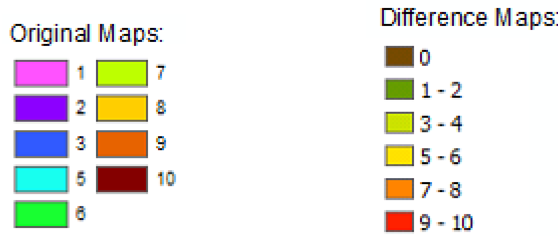


Figure 1 - Classification values and color scheme for visual representation of original rated raster maps (left) and the final difference maps (right) ranging from 1 (low) - 10 (high)

1.3 Results

For each parameter, a brief description of the results is given along with an outline of the original data used to derive the rating values. Data source information for the DRASTIC-Fm study was supplied by Diana Allen (Allen, 2014). Data source information was acquired from Newton and Gilchrist (2010) for the Vancouver Island DRASTIC study (Appendix A, Table A1). A vertical bar graph portraying the differences in grid cell counts between the VI and Fm DRASTIC studies, per rating value from 1-10, is provided for each parameter individually. These graphs quantitatively and visually provide a description of which parameter rating values differ the most in their assignment of DRASTIC values. It is important to note that since the DRASTIC-Fm data have been interpolated and resampled from 5 m grid cells to 100 m, these cell count comparisons provide an estimated representation of the original data. Additionally, since the data sources between the VI and Fm studies differ, covering similar, but not exactly the same area overlying Gabriola Island, there may be a difference in total cell counts per parameter ranging from 0 to 75. For details on exact cell counts see Appendix A, Table A18.

Table 1 displays the grid cell count values for the final difference maps for each parameter; a high cell count value in the higher difference values (5-10) portrays a greater difference in parameter ratings between the VI and Fm studies. Parameters where a high cell count with a difference value of 0 shows no difference in those cells and therefore less difference in rating values between the two studies overall. According to the values given in Table 1, the greatest difference between parameter rating values for each of the studies over Gabriola Island occurs in parameters D, T and S. A moderate difference in cell values occurs in parameter R and I, with little to no difference shown in parameters A and C.

An in depth discussion of how parameters were devised for each DRASTIC study is not included. For reference purposes, Appendix A summarizes the parameter rating tables used for each study. The Fractured Media (Fm) parameter used in the DRASTIC-Fm study is not discussed in Part 1 of this report as it is not applicable to this differences evaluation.

Table 1 - Difference values by cell count of the calculated difference between VI DRASTIC and DRASTIC-Fm rated raster results for each parameter and the percent of overall cells with a difference value of 5 or greater

DIFFERENCE VALUE	D - COUNT	R-COUNT	A-COUNT	S-COUNT	T-COUNT	I-COUNT	C-COUNT
0	1112	3129	132	340	1480	2936	0
1	786	0	5067	3359	714	1102	0
2	1306	0	11	381	944	264	0
3	498	309	0	656	215	504	0
4	692	1801	0	192	1277	369	0
5	448	0	0	46	447	8	0
6	202	0	0	8	108	0	0
7	141	0	0	30	24	0	0
8	10	0	0	177	28	0	0
9	0	0	0	2	8	0	0
10	0	0	0	22	0	0	0
TOTAL CELLS	5195	5239	5210	5213	5245	5183	0
% of Difference cells over 5	15.418672	0	0	5.467101	11.72545	0.154351	0

D - Depth to Water

The original rated raster used in the DRASTIC-Fm study could not be located. The 5m x 5m raster provided was confirmed to represent the depth to water in feet, and was used to create a reclassified rated raster representing the values used in the D rating table for this study. This raster file was used for all successive analysis.

There is quite a bit of difference between studies for parameter D as portrayed below (Figure 2); likely due to the very different types of datasets used to derive this parameter for each study. Refer to Appendix A Tables A1 through A3 for further details on data sources and rating tables.

Raw data sources used to derive D parameter rating values include:
VI DRASTIC

- DEM - BC ILMB, 25 m grid, 1968 - 2002
- Wells - BC WELLS Application, no scale, Jan 2008
- Rivers - BCGS geology map data, 1:50K, 2005
- Lakes - BC Watershed Atlas, 1:50K, 2005

DRASTIC-Fm

- Derived from water-well database, source unspecified, 25m DEM

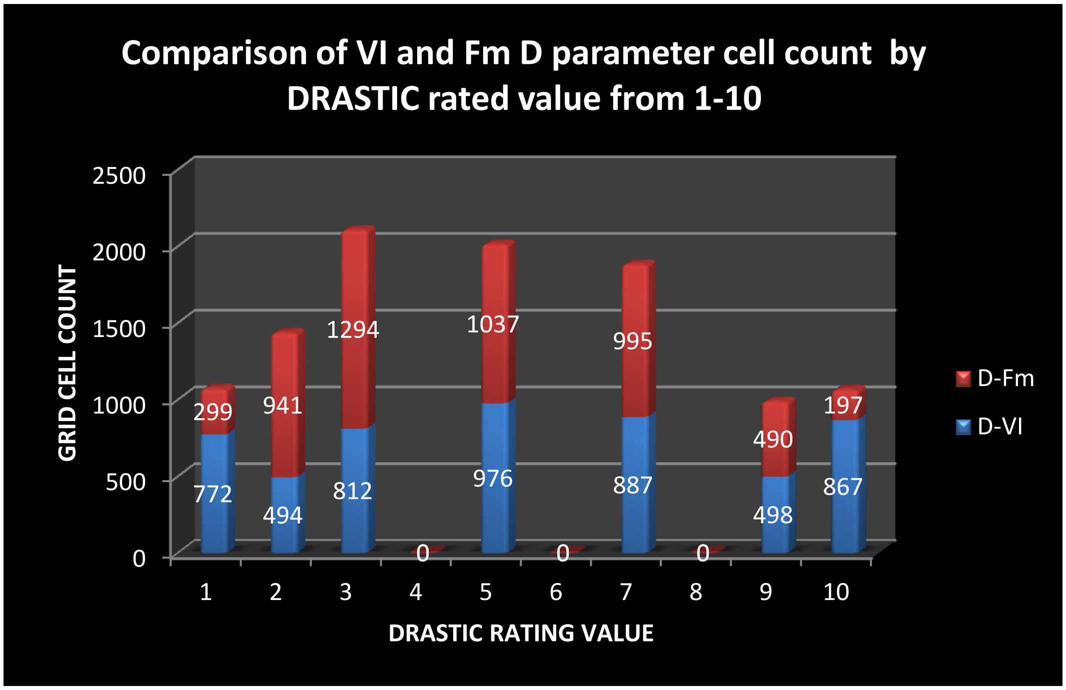


Figure 2 - Graph comparing the difference in grid cell counts for D parameter rating values 1 through 10 between the VI and Fm DRASTIC studies

Both original rasters follow a similar trend; however, at a grid cell size of 100 m, the VI raster seems to provide greater slope detail. See Figures 3-5 for mapped raster representations.

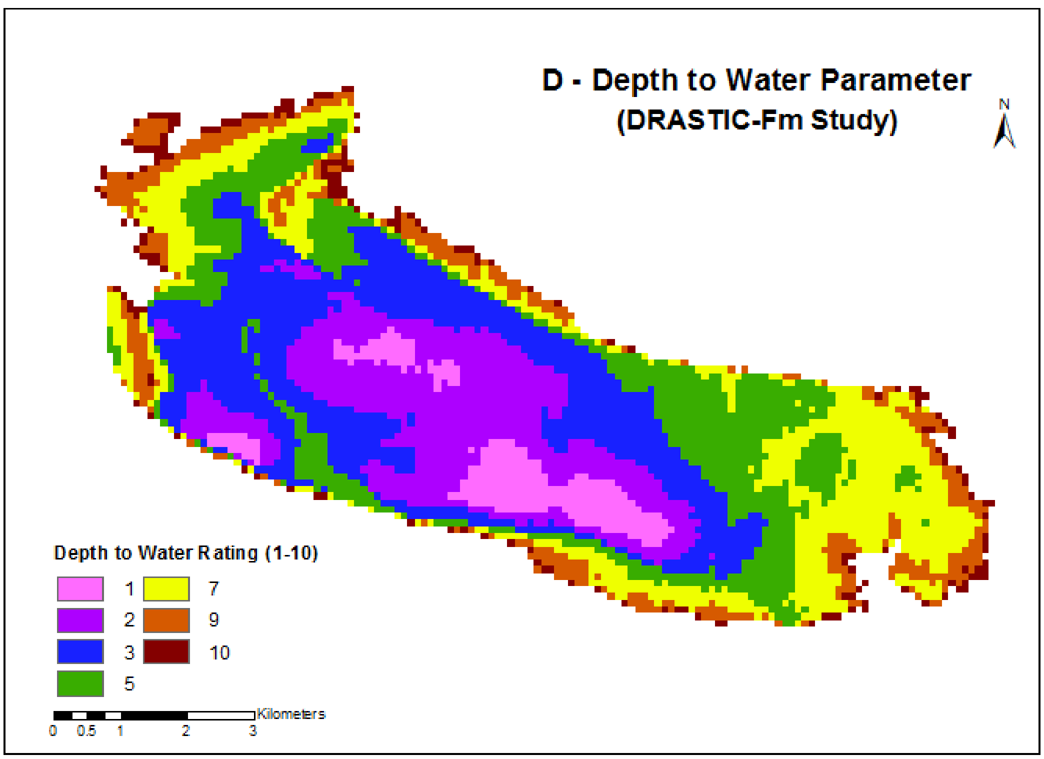


Figure 3 - Map portraying original results of the DRASTIC-Fm rated raster for D

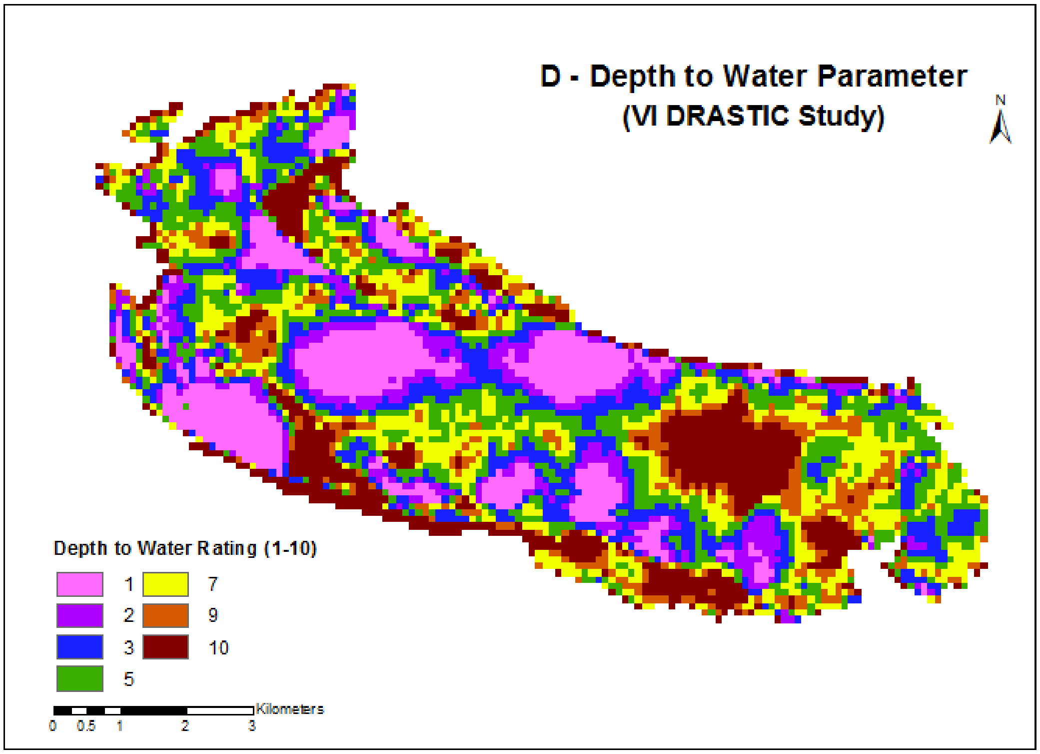


Figure 4 - Map portraying original results of the VI DRASTIC rated raster for D

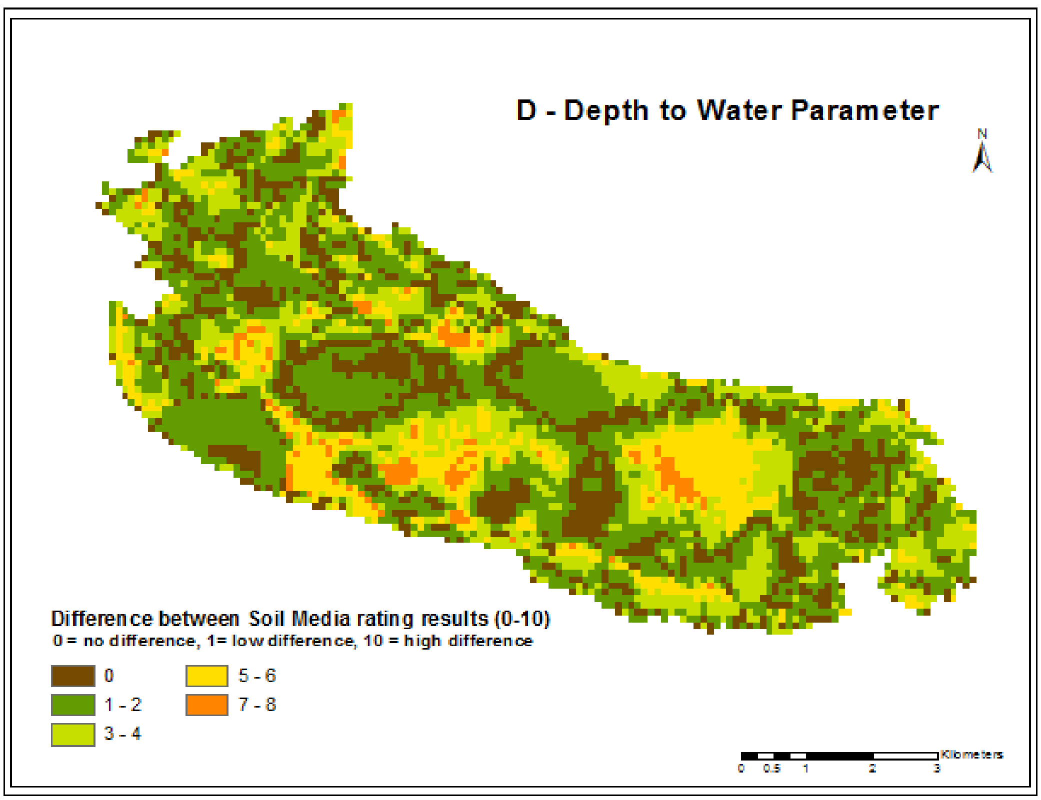


Figure 5 - Map displaying the calculated difference between DRASTIC and DRASTIC-Fm studies final rated rasters for D

R - Net Recharge

R for VI for Gabriola Island was rated at 6, and at 3, 5, and 10 for Fm (Figure 6). This difference in parameter rating values may be due to the larger regional scale at which the VI study was carried out in comparison to the local scale of the Fm study; Fm R data are more detailed whereas the VI R parameter has a single overall rating value of 6. See Figures 7 and 8 for visual representation of the original rated rasters. Little difference exists between the original rated raster values for parameter R. There are no cells calculated with a value of 0 or no change. All difference values are calculated at 1, 3 and 4 with the highest count at a difference value of 1 (Figure 9).

Original data used to derive parameter rating values include:

VI DRASTIC

- Precipitation, ClimateBC, 400m grid, 2006, interpolated for Vancouver Island

DRASTIC-Fm

- Used Victoria airport meteorological station climate data and geologic attributes of water-well database applied to USEPA Hydrologic Evaluation of Landfill Performance model (HELP)

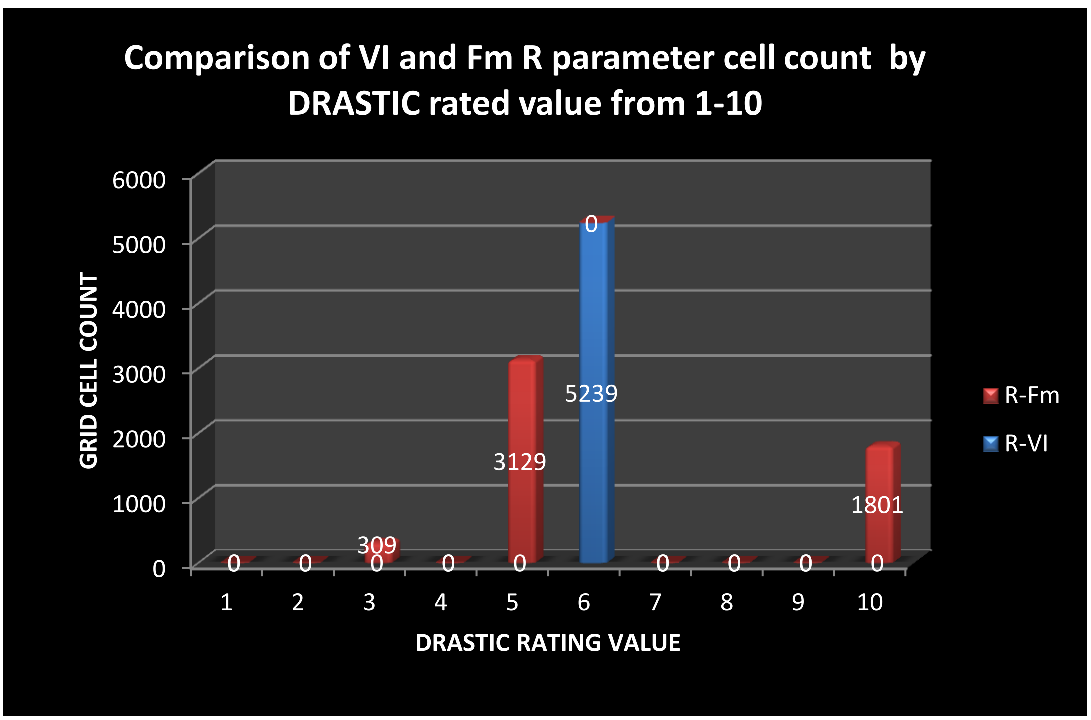


Figure 6 - Graph comparing the difference in grid cell counts for R parameter rating values 1 through 10 between the VI and Fm DRASTIC studies

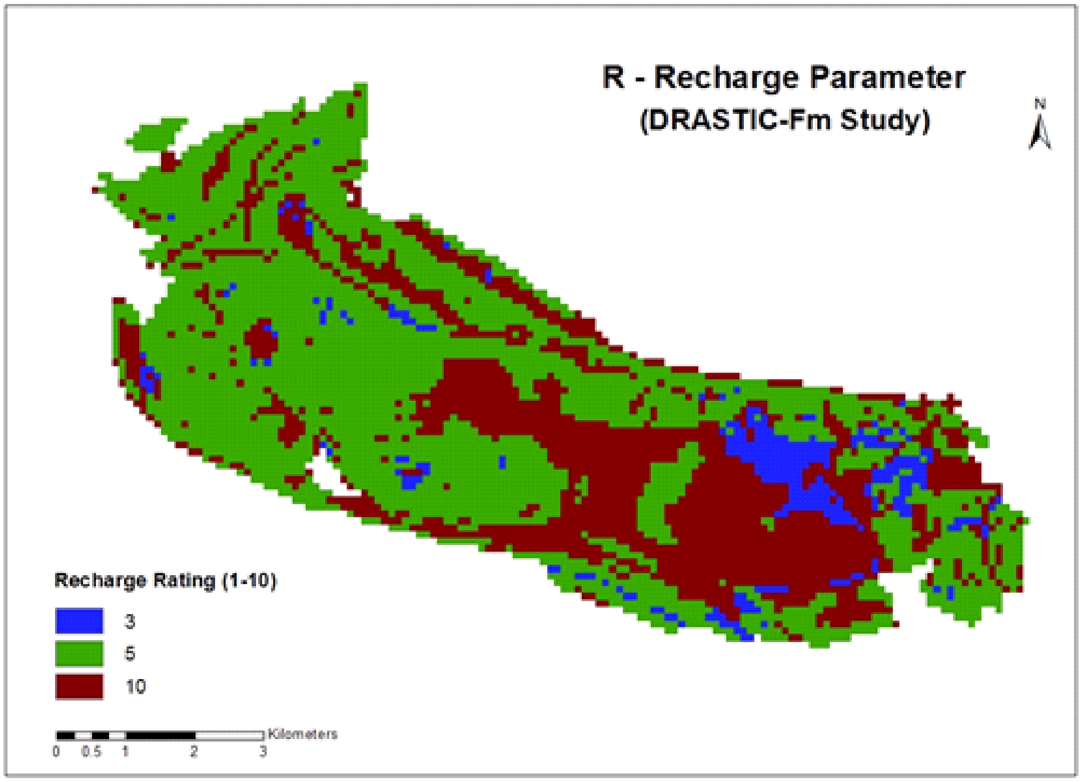


Figure 7 - Map portraying original results of the DRASTIC-Fm rated raster for R

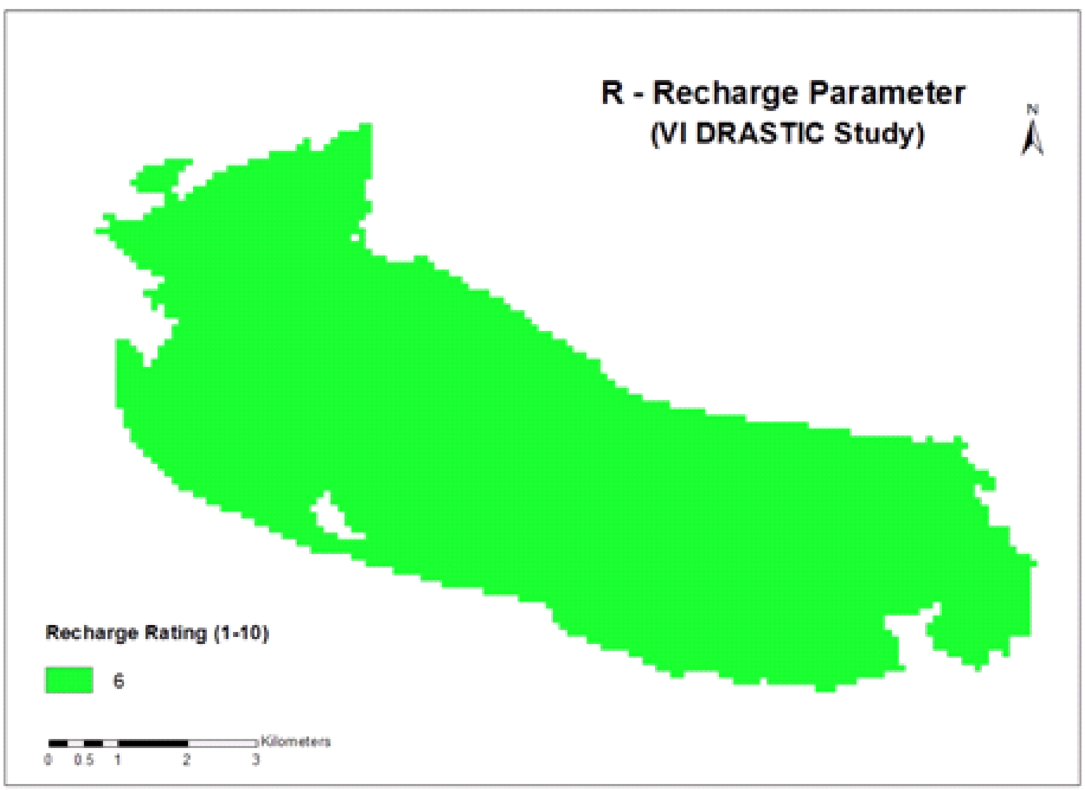


Figure 8 - Map portraying original results of the VI DRASTIC rated raster for R

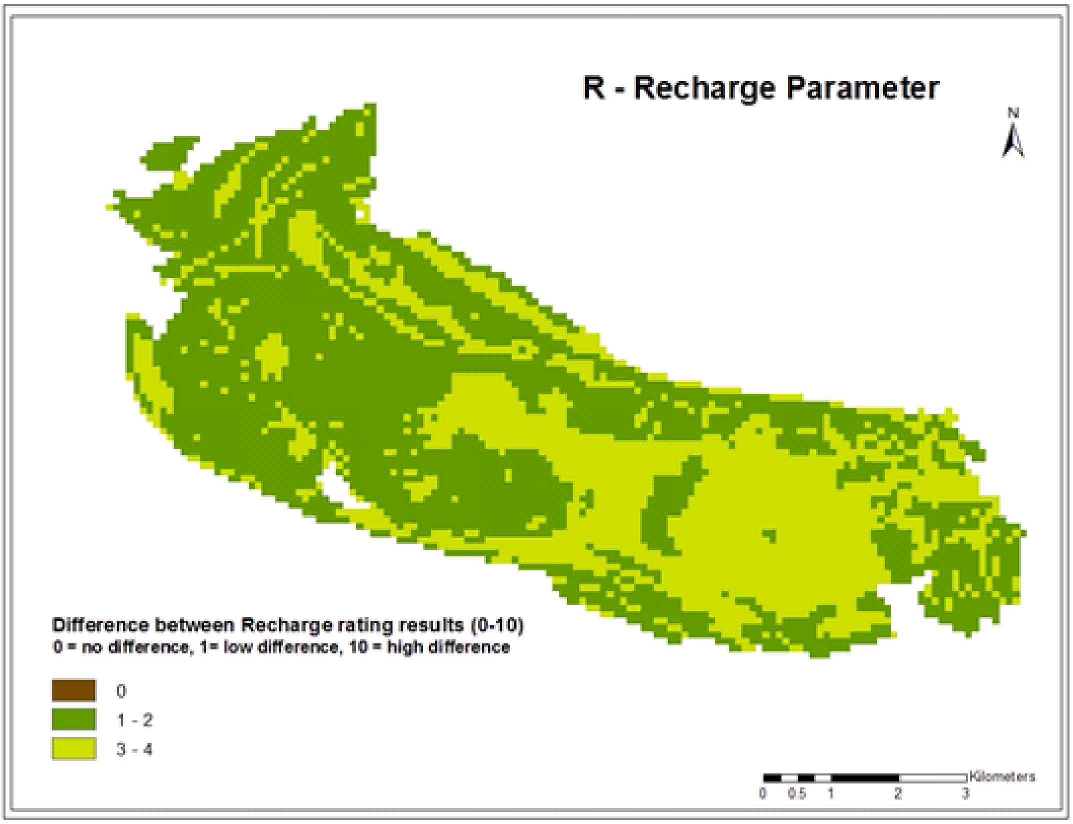


Figure 9 - Map displaying the calculated difference between DRASTIC and DRASTIC-Fm studies final rated rasters for R

A - Aquifer Media

Resulting difference values are low for parameter A. The VI study rated Gabriola Island at 5, 6 and the Fm study at 4, 5, 6, 7 (Figure 10). Difference values range from 0 or no change to 2, with the highest cell count at a difference of 1. Figures 11 through 13 display a mapped representation of the original rated rasters and the difference values.

Original data used to derive parameter rating values include:

VI DRASTIC

- Wells information from BC WELLS Application, no scale, January 2008
- Aquifer polygons and worksheet from BC WELLS Application, no scale, 2007 polygons, 1995-2004 worksheets

DRASTIC-Fm

- Bedrock geology dataset for Gulf Islands and field observations.

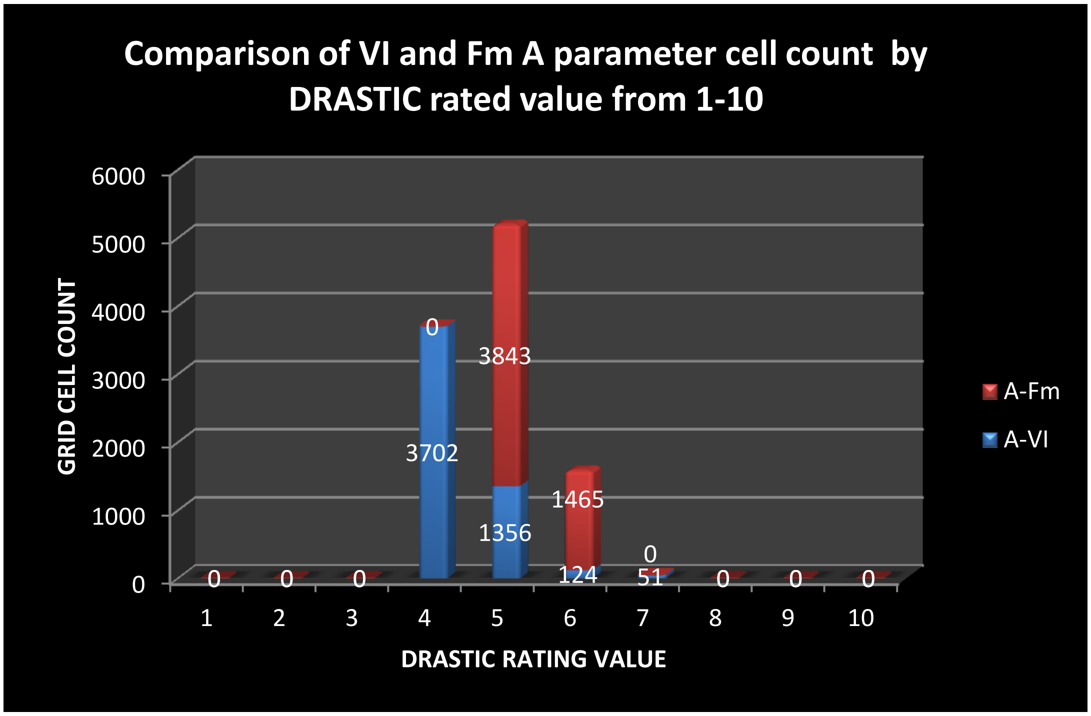


Figure 10 - Graph comparing the difference in grid cell counts for A parameter rating values 1 through 10 between the VI and Fm DRASTIC studies

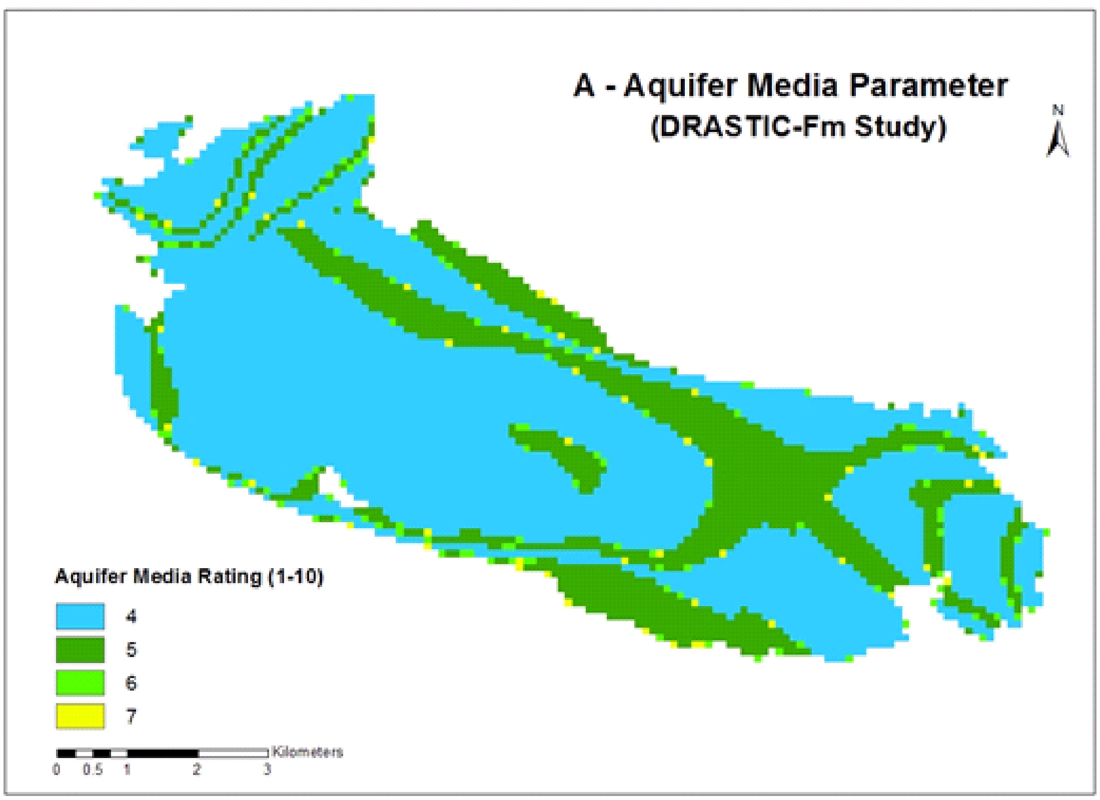


Figure 11 - Map portraying original results of the DRASTIC-Fm rated raster for A

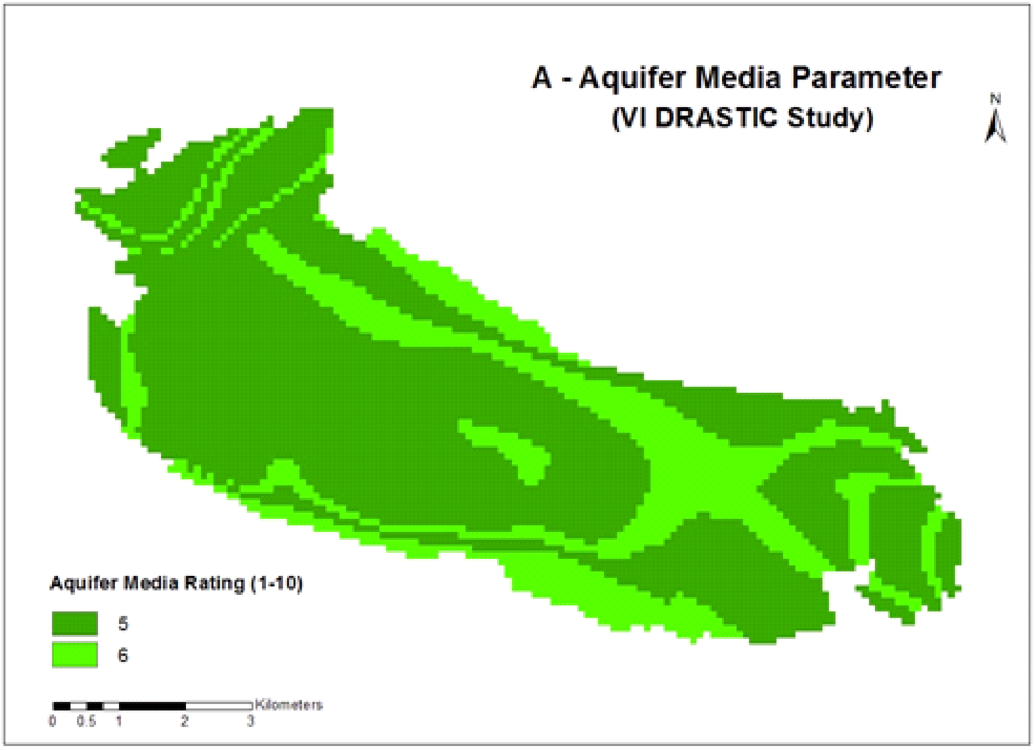


Figure 12 - Map portraying original results of the VI DRASTIC rated raster for A

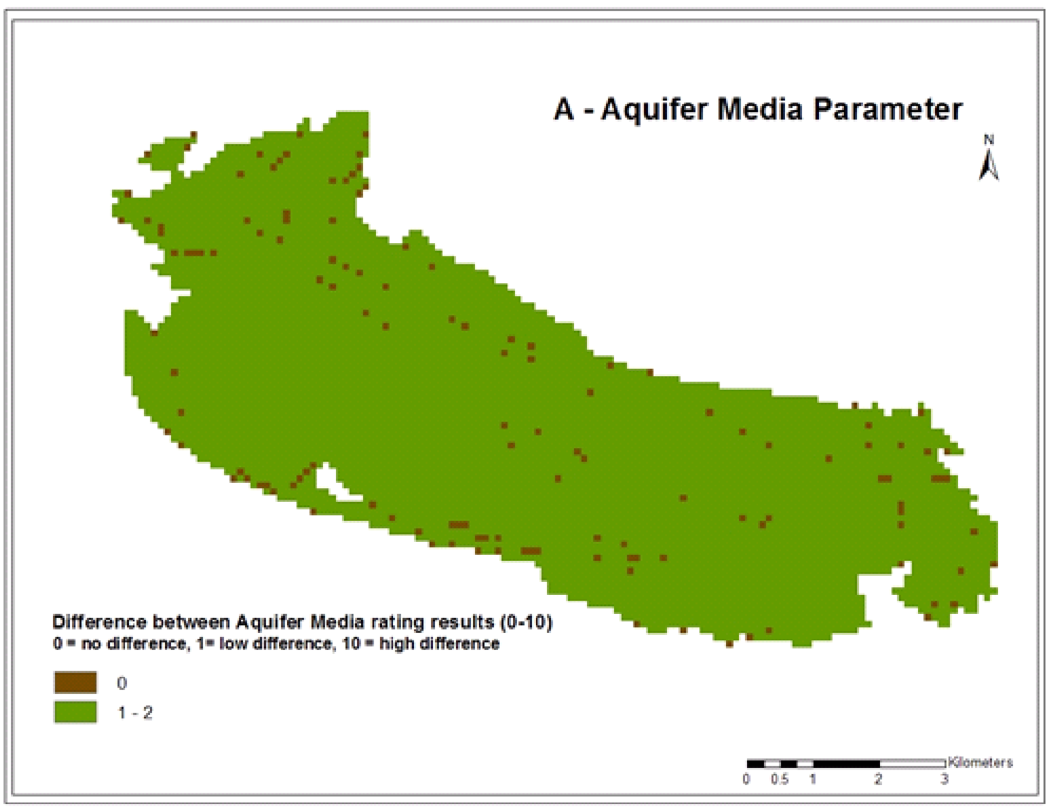


Figure 13 - Map displaying the calculated difference between DRASTIC and DRASTIC-Fm studies final rated rasters for A

S - Soil Media

There exists a full range of difference values for parameter S between the two studies, although the majority of differences are captured between difference values of 0-4 (Table 1). Both original rated rasters seem to capture similar features of distinction, but rate them differently (Figures 14-16). See Appendix A, Tables A8 and A9 for rating table references. Of visual prominence is a large portion of the island that the VI study rates at 8 (orange), whereas the Fm study rates it at 7 (yellow). Additionally, there is a large area on the south-west part of the island that the VI study rates at 5 (green), but the Fm rates at 8 (orange). Cells of high difference values, portrayed in red in Figure 17, seem to occur for the most part in cells of overlap where no data exist from the Fm study and a rating value of 10 was given in the VI study.

Original data used to derive parameter rating values include:

VI DRASTIC

- Soil Survey
  - BC44 (Jungen 1985), 1:100K, 1985, National Soils Database detailed soil surveys with soil texture and drainage
  - BC43-4 (Kenney et al. 1989), 1:20K, 1989, National Soils Database
  - CAPAMP Vanc Is, 1:20K, 1985-89, BC CAPAMP soil surveys

DRASTIC- Fm

- Soil datasets Agriculture Canada (van Vilet et al. 1987, 1991; Kenny et al. 1988, 1990; Green et al. 1989)

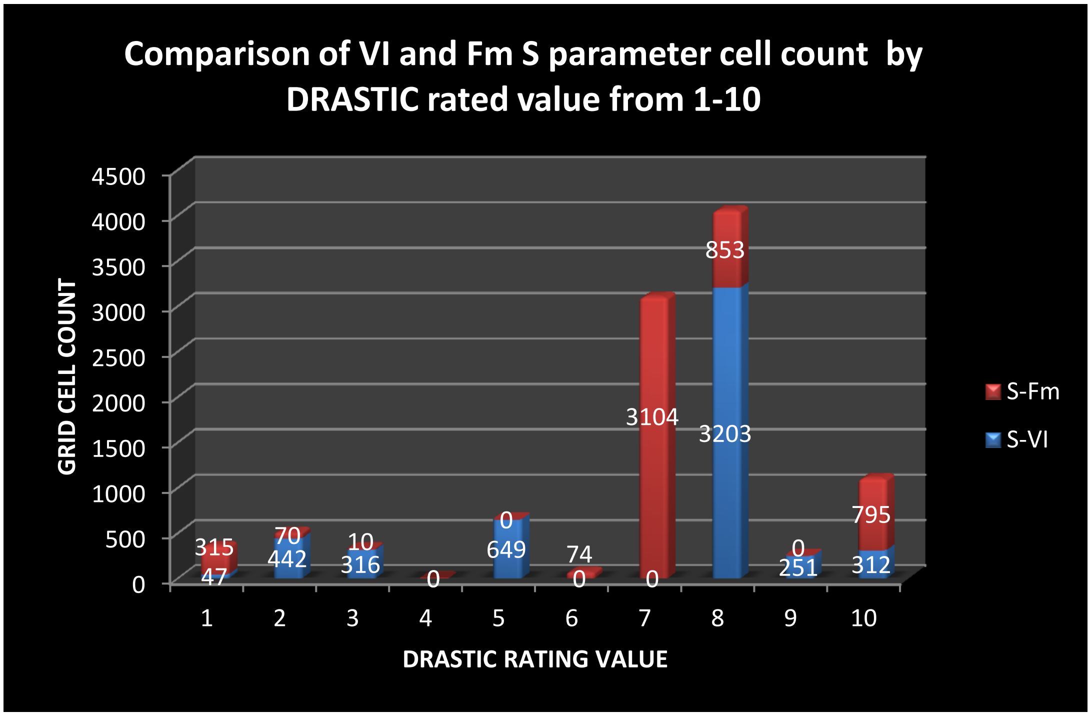


Figure 14 - Graph comparing the difference in grid cell counts for S parameter rating values 1 through 10 between the VI and Fm DRASTIC studies

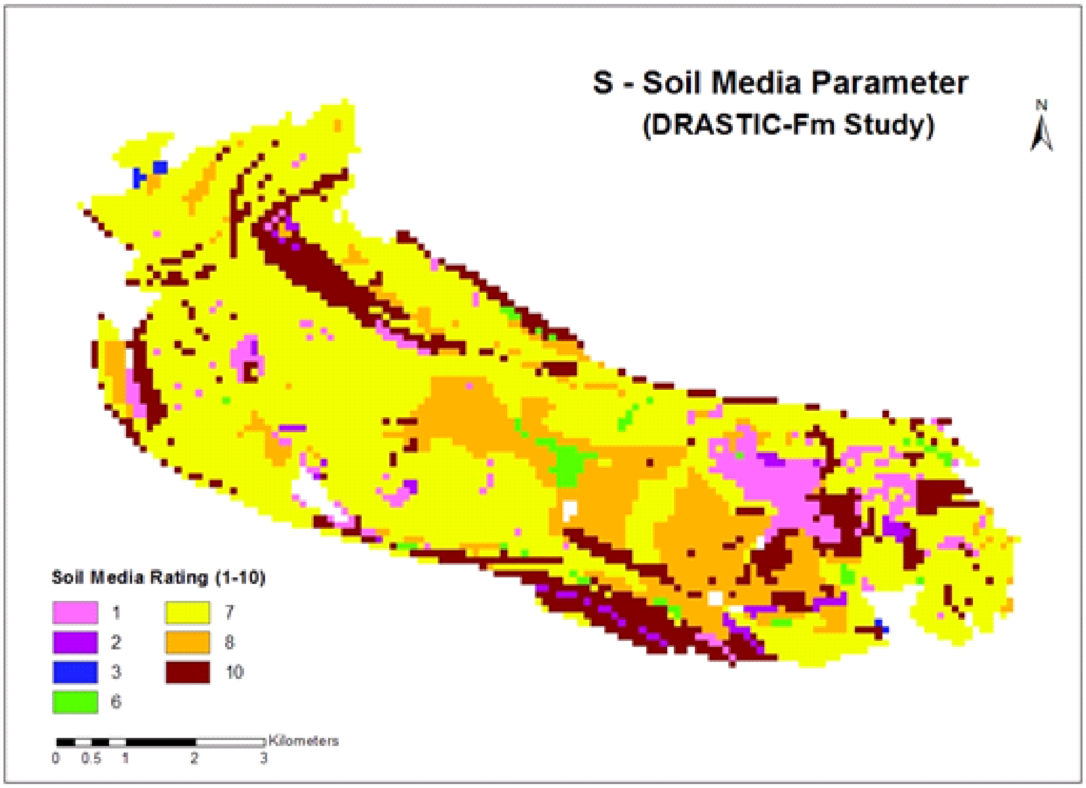


Figure 15 - Map portraying original results of the DRASTIC-Fm rated raster for S

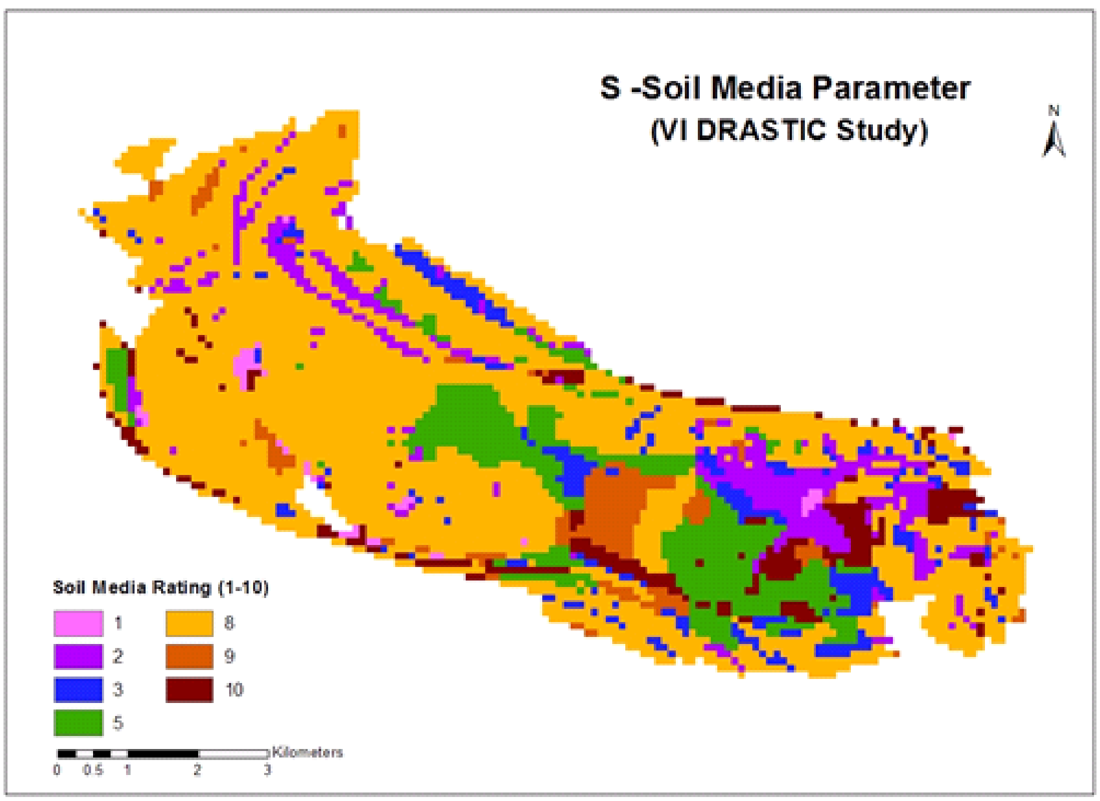


Figure 16 - Map portraying original results of the VI DRASTIC rated raster for S

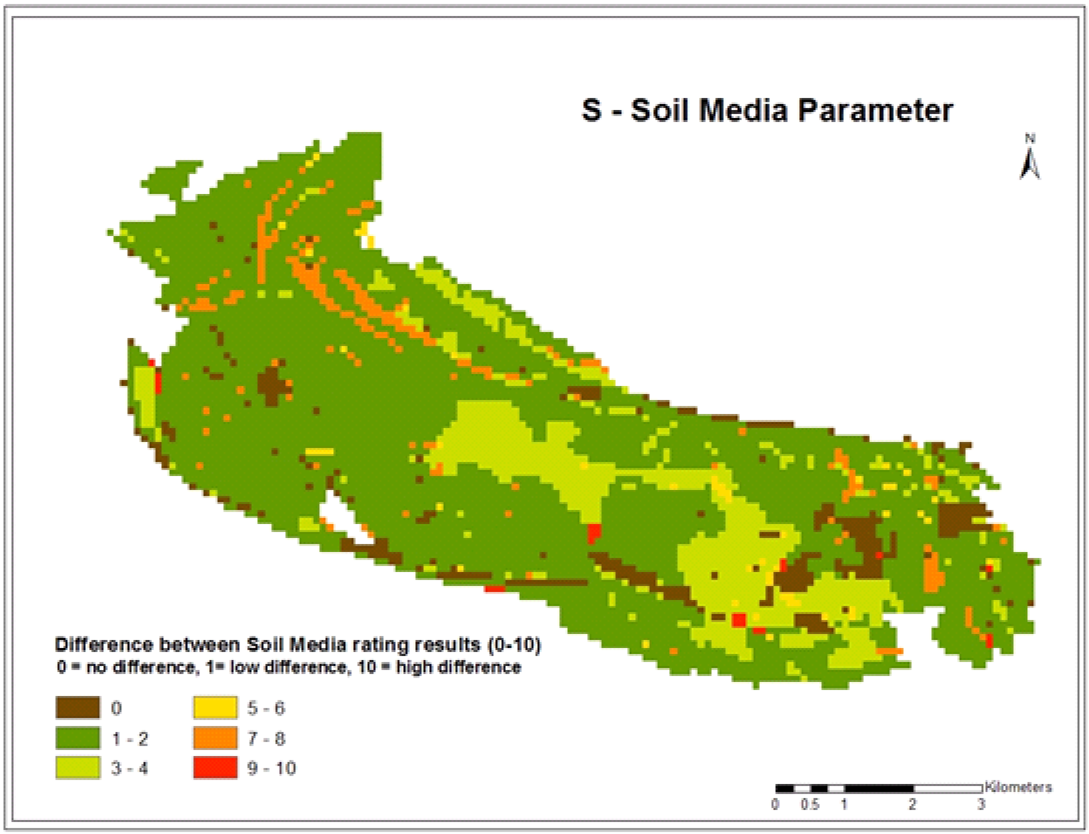


Figure 17 - Map displaying the calculated difference between DRASTIC and DRASTIC-Fm studies final rated rasters for S

T - Topography

There is a large range of difference values for parameter T between the two studies (Figure 21). Both original rated rasters capture some similar features of distinction such as shoreline slope, but vary greatly in other features portrayed and the rating values assigned (Figures 18-20). When examining the rating tables used for both of these studies, differences arise between the percent of slope values assigned to rating values 1-10. The VI study rating table is identical to the original DRASTIC methodology (Aller et al., 1987); whereas the Fm study rating table delineates percent of slope values differently. See Appendix A, Tables A10 and A11 for rating table reference. The majority of difference seen in this parameter seems to come from the differing data sources utilized to derive these parameters.

Original data used to derive parameter rating values include:

VI DRASTIC

- Digital Elevation Model, BC ILMB, 25m grid, 1968-2002

DRASTIC-Fm

- Due to coherence with S parameter and detailed scale, soil datasets were used since each polygon had slope description attribute. Soil datasets Agriculture Canada (van Vilet et al. 1987, 1991; Kenny et al. 1988, 1990; Green et al. 1989)

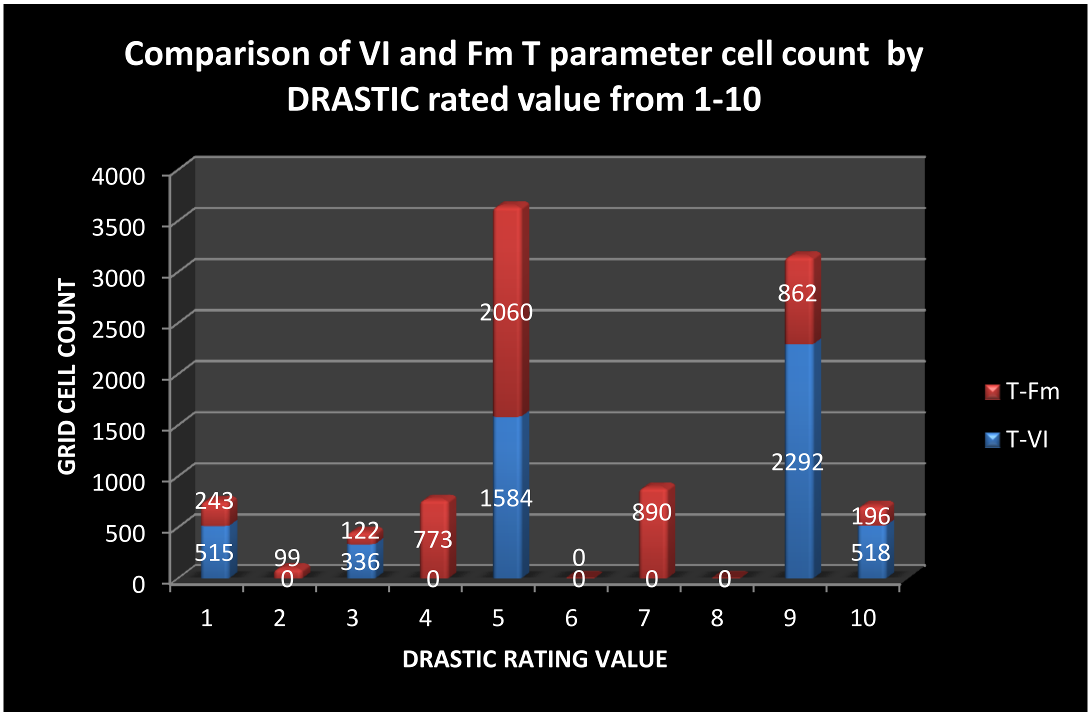


Figure 18 - Graph comparing the difference in grid cell counts for T parameter rating values 1 through 10 between the VI and Fm DRASTIC studies

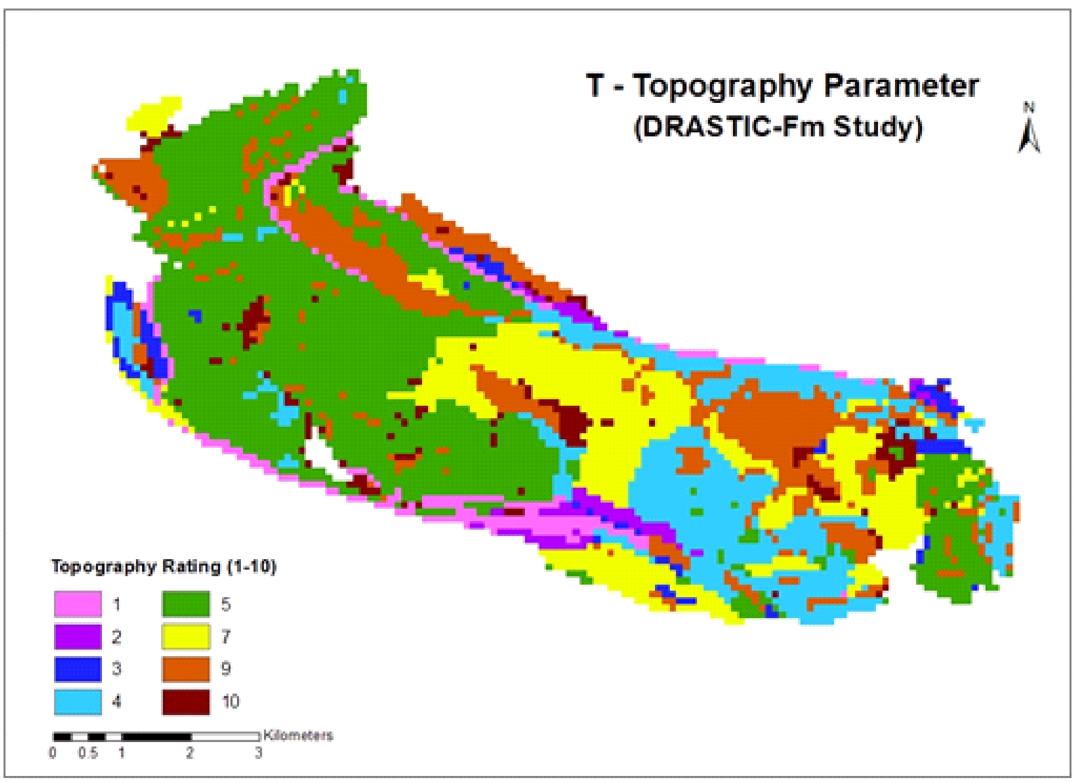


Figure 19 - Map portraying original results of the DRASTIC-Fm rated raster for T

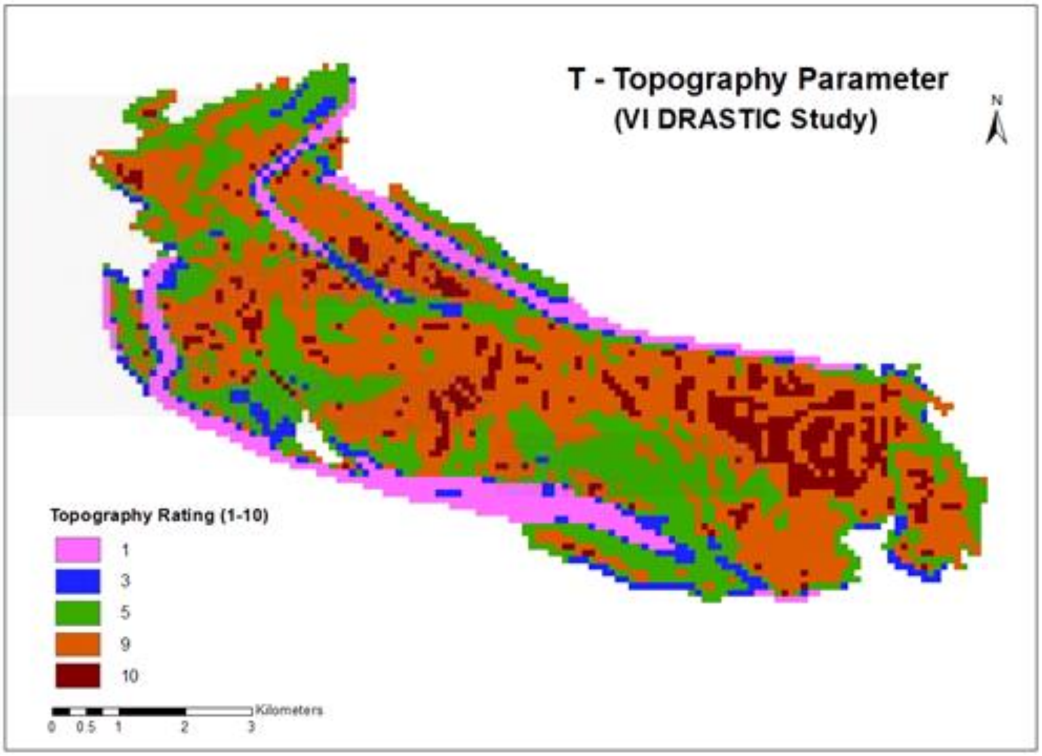


Figure 20 - Map portraying original results of the VI DRASTIC rated raster for T

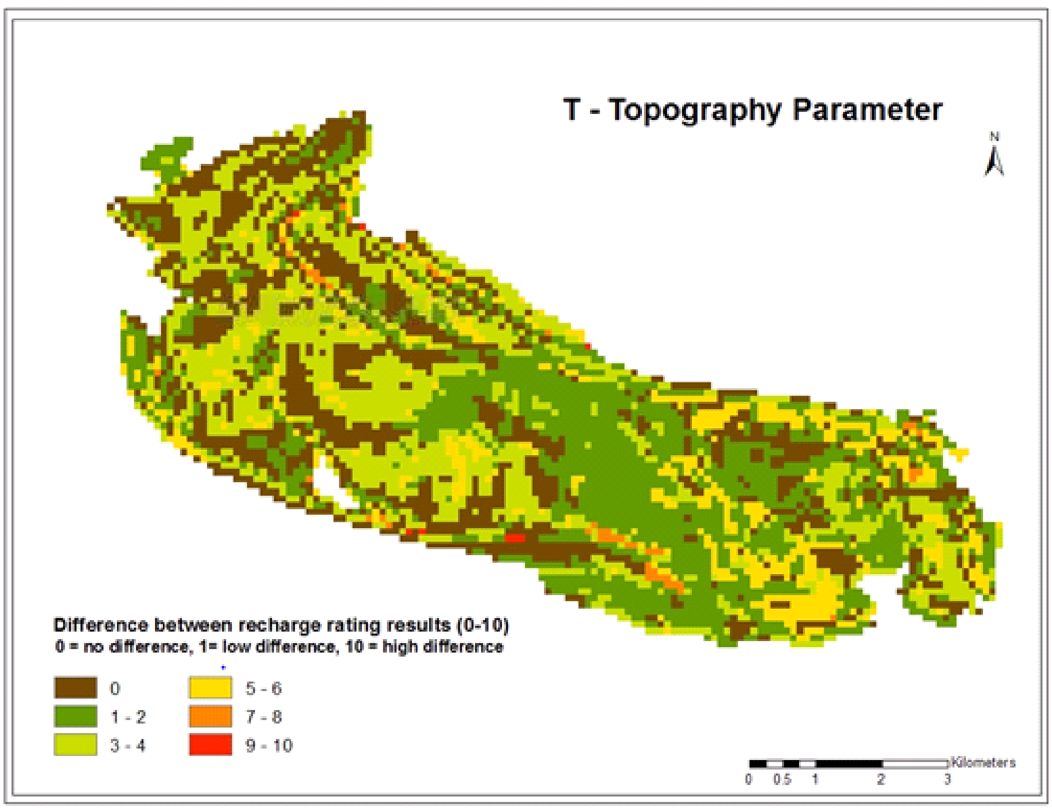


Figure 21 - Map displaying the calculated difference between DRASTIC and DRASTIC-Fm studies final rated rasters for T

I - Impact of Vadose Zone

The original rasters for both studies seem to follow a similar underlying trend, with the Fm raster portraying greater detail in certain areas such as the south-west island and coastlines. The greatest difference between the two rasters is found between difference values of 0 through 4 (Figure 25). The rating values for parameters A and I were given the same rating scheme (5-6) in the VI DRASTIC study. The DRASTIC-Fm datasets portray more detail giving rating values from 1 through 9 (Figures 22-24).

Original data used to derive parameter rating values include:

VI DRASTIC

- Wells, BC WELLS Application, January 2008
- Bedrock geology maps, BCGS & GSC, 1:250K (BCGS) 1:50K (GSC), 2005
- Aquifer polygons and worksheets, BC WELLS Application, 2007
- Terrain map, Forest Renewal BC, 1:50K, 1975-1983

DRASTIC-Fm

- Soil datasets Agriculture Canada (van Vilet et al. 1987, 1991; Kenny et al. 1988, 1990; Green et al. 1989)
- Derived from water-well database, source unspecified, and 25m DEM

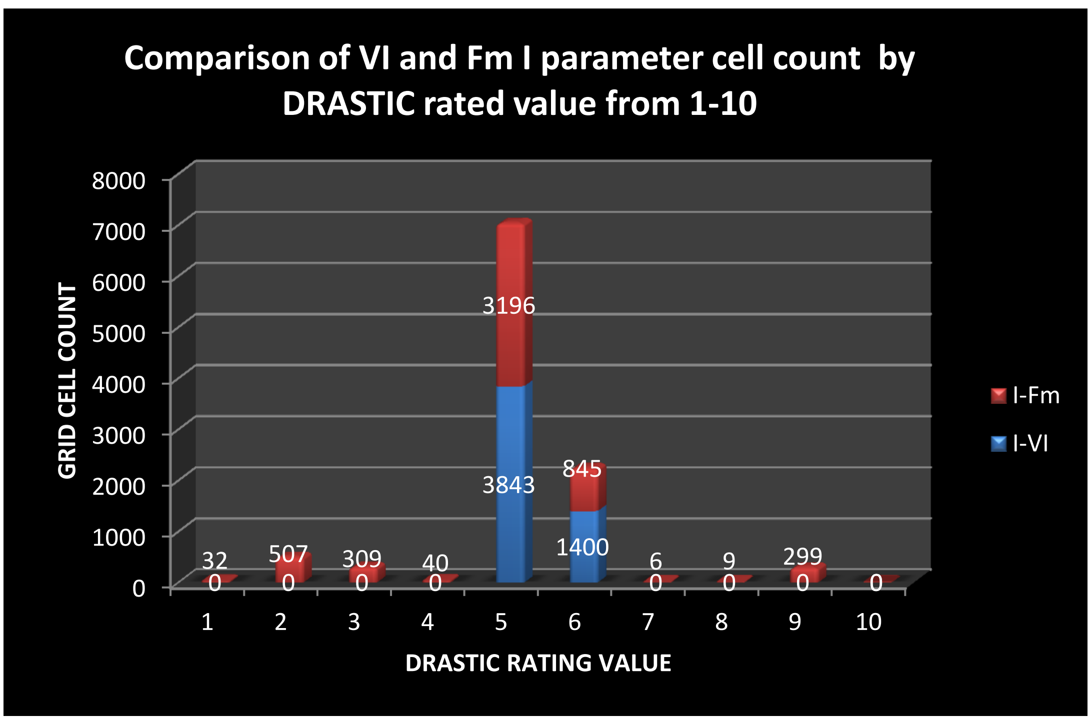


Figure 22 - Graph comparing the difference in grid cell counts for I parameter rating values 1 through 10 between the VI and Fm DRASTIC studies

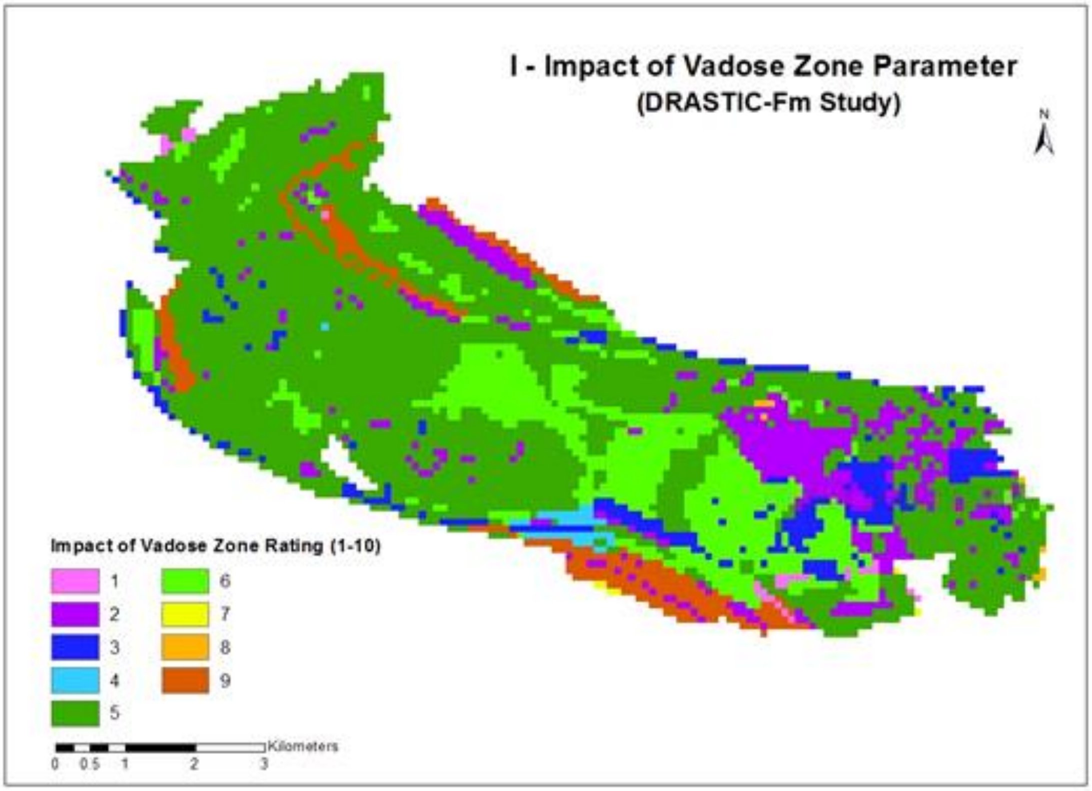


Figure 23 - Map portraying original results of the DRASTIC-Fm rated raster for I

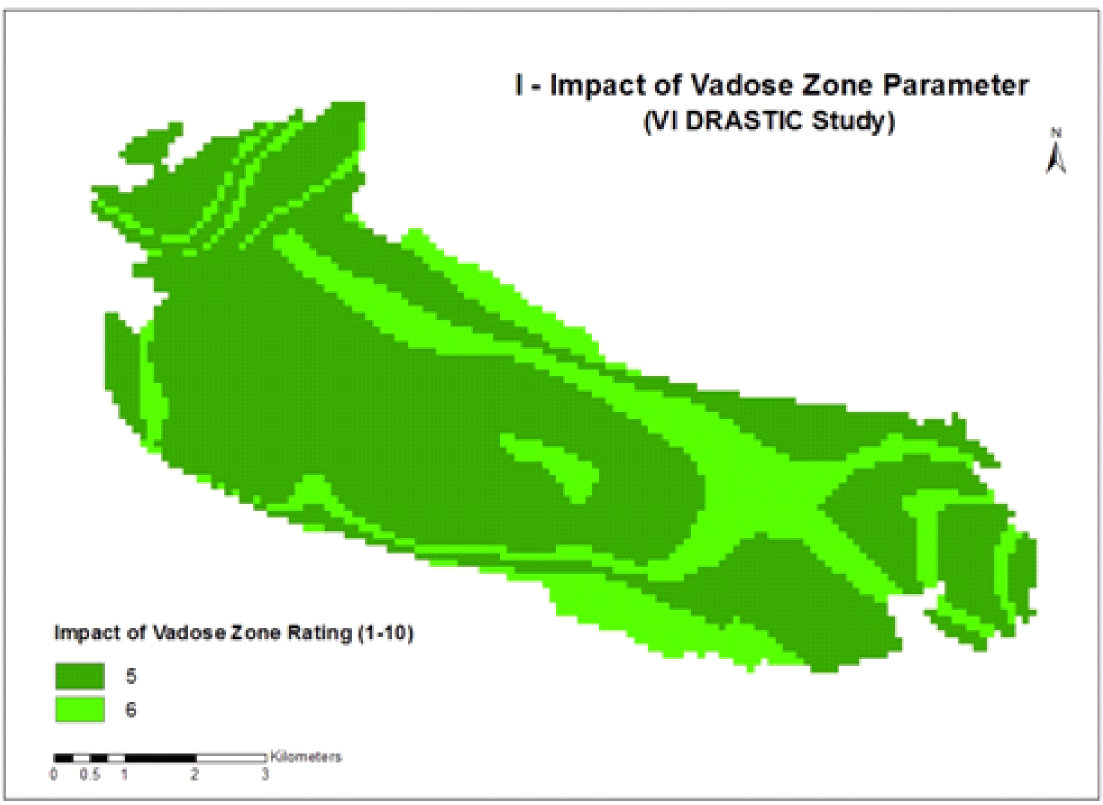


Figure 24 - Map portraying original results of the VI DRASTIC rated raster for I

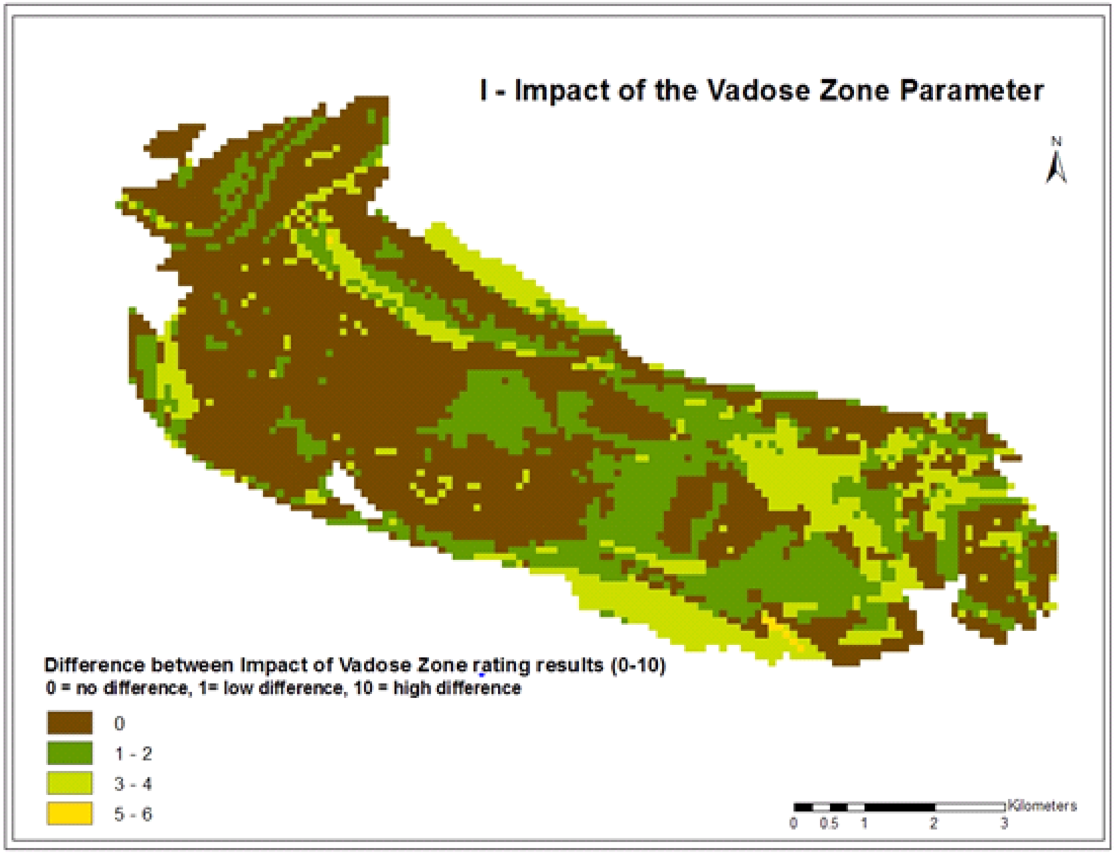


Figure 25 - Map displaying the calculated difference between DRASTIC and DRASTIC-Fm studies final rated rasters for I

C - Hydraulic Conductivity

Both studies set a C parameter rating value of 1 for Gabriola Island, therefore there is no difference between the two studies. Visual representation of this lack of difference is displayed in Figures 26-28.

Original data used to derive parameter rating values include:

VI DRASTIC

- Wells, BC WELLS Application, January 2008
- Bedrock geology maps, BCGS & GSC, 1:250K (BCGS) 1:50K (GSC), 2005
- Aquifer polygons and worksheets, BC WELLS Application, 2007
- Hydrogeological consulting reports, various sources, 1963-2007

DRASTIC-Fm

- Based on well pumping tests performed and Bedrock geology dataset for Gulf Islands

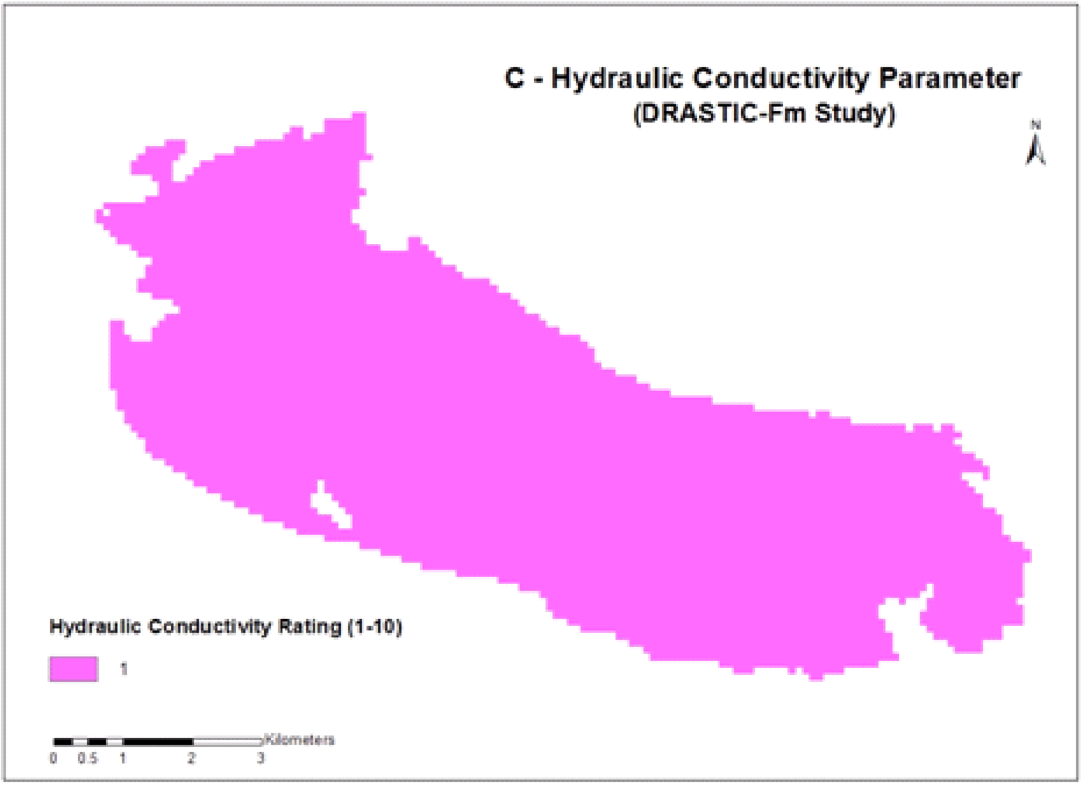


Figure 26 - Map portraying original results of the DRASTIC-Fm rated raster for C

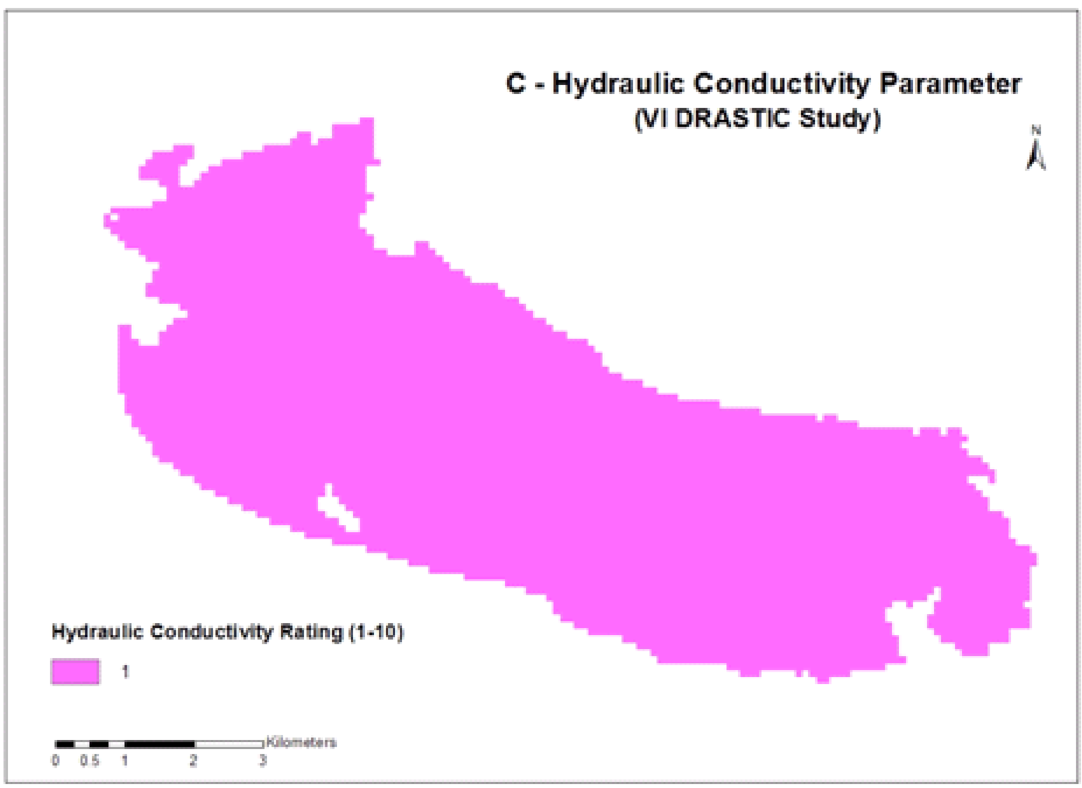


Figure 27 - Map portraying original results of the VI DRASTIC rated raster for C

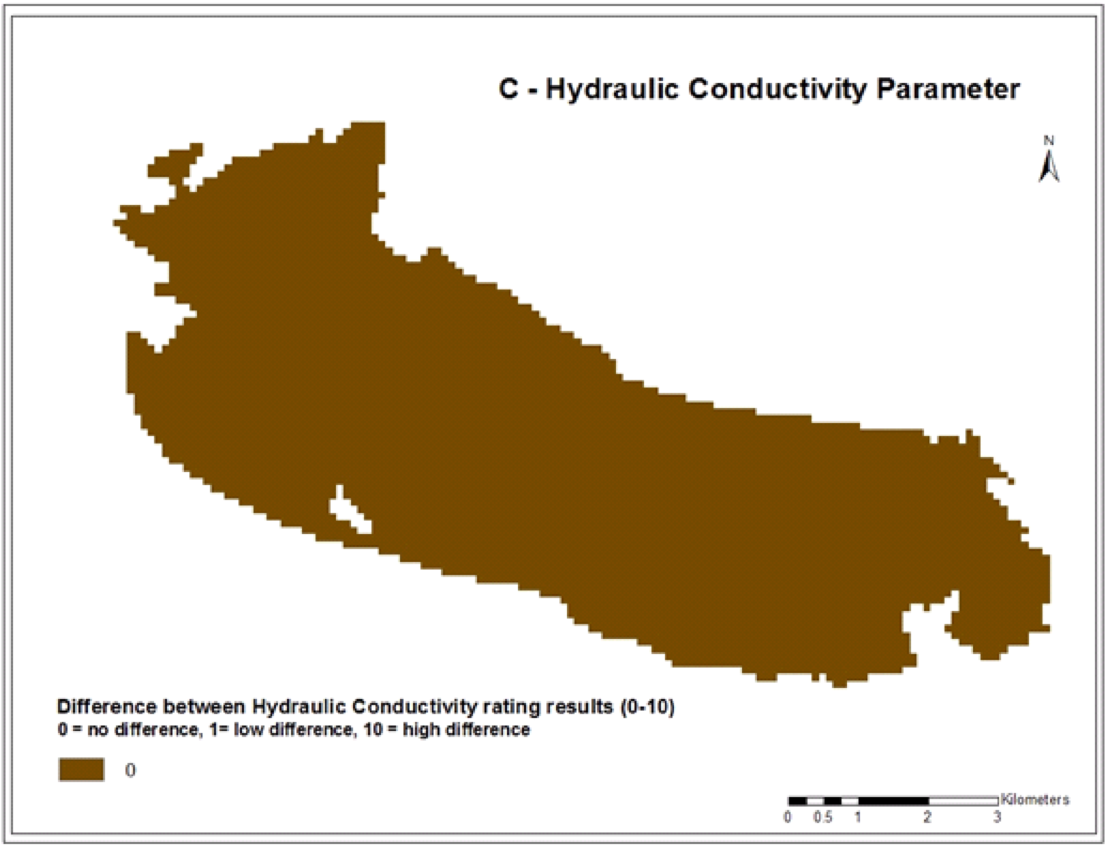


Figure 28 - Map displaying the calculated difference between DRASTIC and DRASTIC-Fm studies final rated rasters for C

1.4 Discussion

Parameters D, S, T and I showed the greatest range of difference between the Vancouver Island DRASTIC 2010 study and the Gulf Island DRASTIC-Fm 2007 study rating methodologies, based on the calculated difference values and respective mapped representations. Parameters R, A and C show little to no difference between studies. Overall the DRASTIC-Fm data provide a more detailed representation of the aquifer parameter characteristics of evaluation in DRASTIC methodology even when resampled to a 100 m grid cell size. This observation of greater detail is due to the local scale at which that study was carried out, compared to the regional scale of the Vancouver Island DRASTIC study.

Part 1 of this report has described the results comparing the differences in methodology between the two studies of interest. Evaluation of differences between these two studies may be of use in the understanding and application of the intrinsic aquifer susceptibility ratings calculated and the influencing hydrogeological features represented by both studies respectively. These results were used in discussion with project partners and combined with their expertise to project and outline subsequent steps in this project.

PART 2.0 Incorporating Fm susceptibility parameter rating into C parameter for DRASTIC-Fm study

2.1 Introduction

The DRASTIC method adopted by the Province of British Columbia (BC) for assessing the intrinsic susceptibility (commonly referred to as the vulnerability) of aquifers in BC, employs the standard DRASTIC range of 23-230. In the DRASTIC-Fm approach, an additional parameter Fm (Fractured Media) was included, which resulted in a larger range of 26-260. In order to align these two approaches for the southern Gulf Islands, different options were explored for incorporating the Fm parameter into the original DRASTIC framework. Specifically, Fm was incorporated into the existing Hydraulic Conductivity (C) parameter such that the overall range would be consistent with the DRASTIC standard range.

This section describes the results of a comparison of different approaches for incorporating Fm into C. Final data and results are 5m x 5m cell size and projected as NAD83 Albers.

2.2 Combining and Reclassifying the Rated Rasters

Hydraulic Conductivity (C) ratings range from 1-10; for the entire southern Gulf Islands C was given a rated value of 1, whereas Fm ranged from 1-9.

Two approaches were taken to work the rating values of Fm into C.

1. **Add approach**: involved adding the values of Fm to the existing areas where the rating value of C was given a 1. This approach would increase cells where Fm has 0 rating and C has a rating by 1 (since all of C is rated at 1), and leave cells where Fm has 0 rating as a rated value of 1 (as a rating of 1 from C exists). This approach is referred to as 'Add' approach in the tables and figures below.

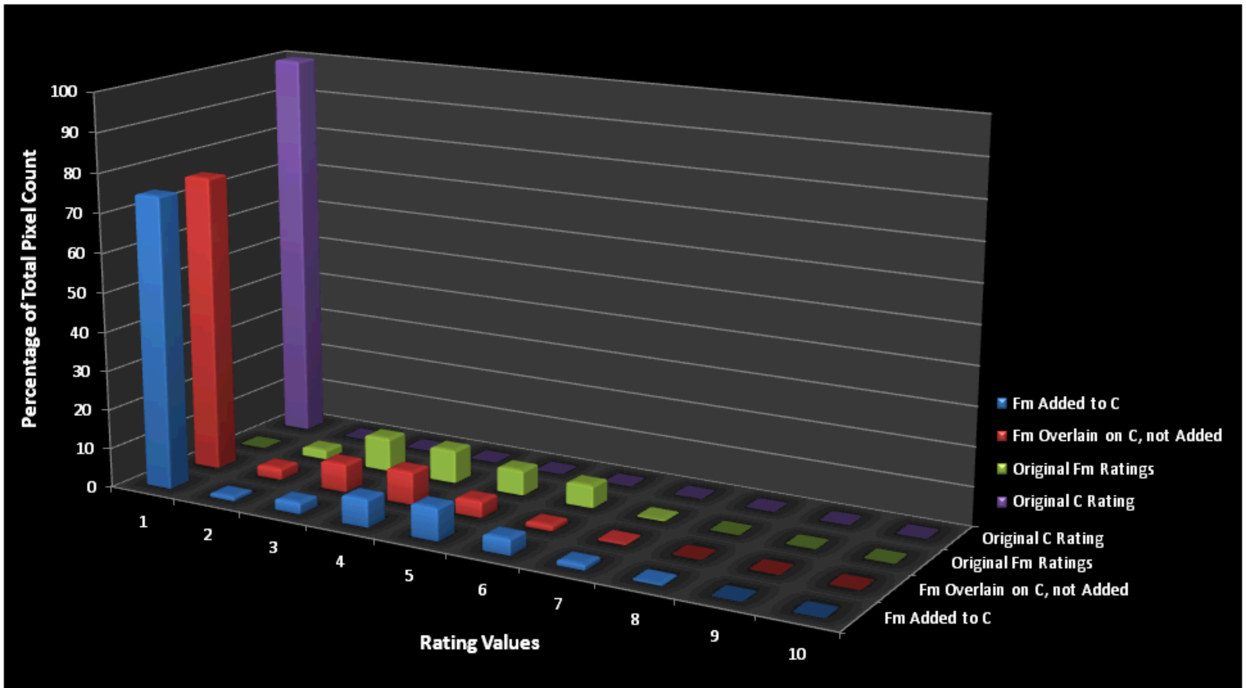
2. **Overlain approach:** involved overlaying the values of Fm on top of the C values. Thus, the Fm cell values stay as they were originally rated; the areas where both Fm and C are rated at 1 stay as 1, and areas where C is 1 and Fm has 0 rating result in a rating of 1. This approach is referred to as 'Overlain' in the tables and figures below.

Both approaches involved combining the Fm and C rated rasters and then reclassifying them based on adding or overlaying the Fm values, respectively. Table 2 shows the value deduction of the two resulting rated rasters for both approaches.

Table 2 - Displays Fm with C combined raster and resulting C raster reclassified with Fm values both Added and Overlain. 0 values represent cells with no rated value, or no data.

'C_Fm_Combo_5m'			'C_Reclass_Add	'C_Reclass_Overlain
VALUE	C_RASTER	FM_RASTER	VALUE	VALUE
1	1	0	1	1
2	1	2	3	2
3	1	4	5	4
4	1	5	6	5
5	1	3	4	3
6	1	6	7	6
7	1	7	8	7
8	1	1	2	1
9	1	8	9	8
10	1	9	10	9
11	0	4	4	4
12	0	3	3	3
13	0	0	0	0

Figure 29 displays the percent coverage of rated values (1-10) comparing side-by-side the original C and Fm rated rasters, as well as the 2 newly reclassified C rated rasters with Fm Added and Overlain, respectively.



Data Table: Parameters with rating values 1-10 by percent (%) of overall rated parameter proportion

	1	2	3	4	5	6	7	8	9	10
Fm Added to C	74.7147	1.0693	2.8969	7.0952	8.2809	4.1072	1.3759	0.3611	0.0471	0.0319
Fm Overlain on C, not Added	75.7841	2.8799	7.1119	8.2812	4.1072	1.3759	0.3611	0.0471	0.0319	0
Original Fm Ratings	0	2.3617	8.5510	8.4351	6.3860	5.6807	0.2930	0	0	0
Original C Rating	100	0	0	0	0	0	0	0	0	0

Figure 29 - Comparison of original Fm and C rated rasters and the 2 new reclassified C rasters with Fm added and overlain, respectively, by their rated values plotted by percent of total cell coverage

2.2.1 Map Results

A few visualizations of the map results are provided below. Figures 30 and 31 display the original Fm and C parameter rated rasters for the original study area of Gabriola Island. Figures 32 and 33 display the newly reclassified rasters for Gabriola Island, simply to demonstrate the increase in fracture rated values by 1 for the 'Adding' approach, otherwise little difference is seen.

Figures 34 and 35 display the 2 new reclassified rated rasters for all of the southern Gulf Islands. In some areas where the Fm and C values were rated as 1 and left as 1 in the overlay approach, fractures are lost, whereas in the add approach fractures are more prominent given a value of 2. This observation is influential in the final calculations of the intrinsic susceptibility values discussed in the next sub-section.

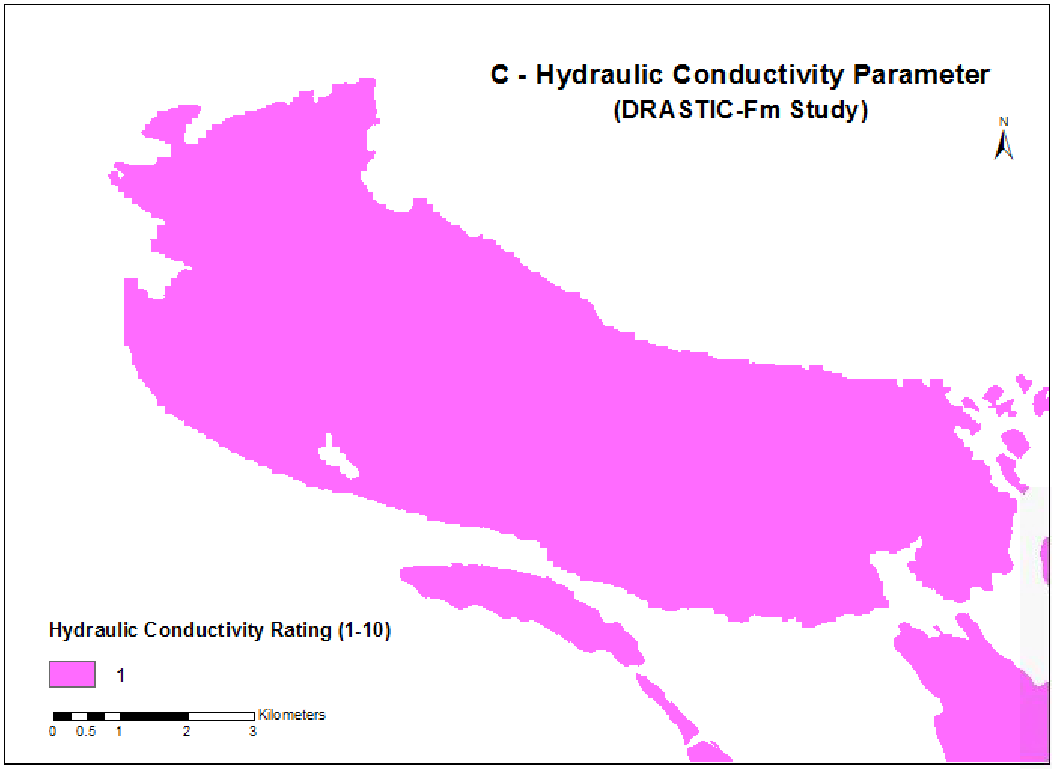


Figure 30 - Original rated raster for C parameter, Gabriola Island

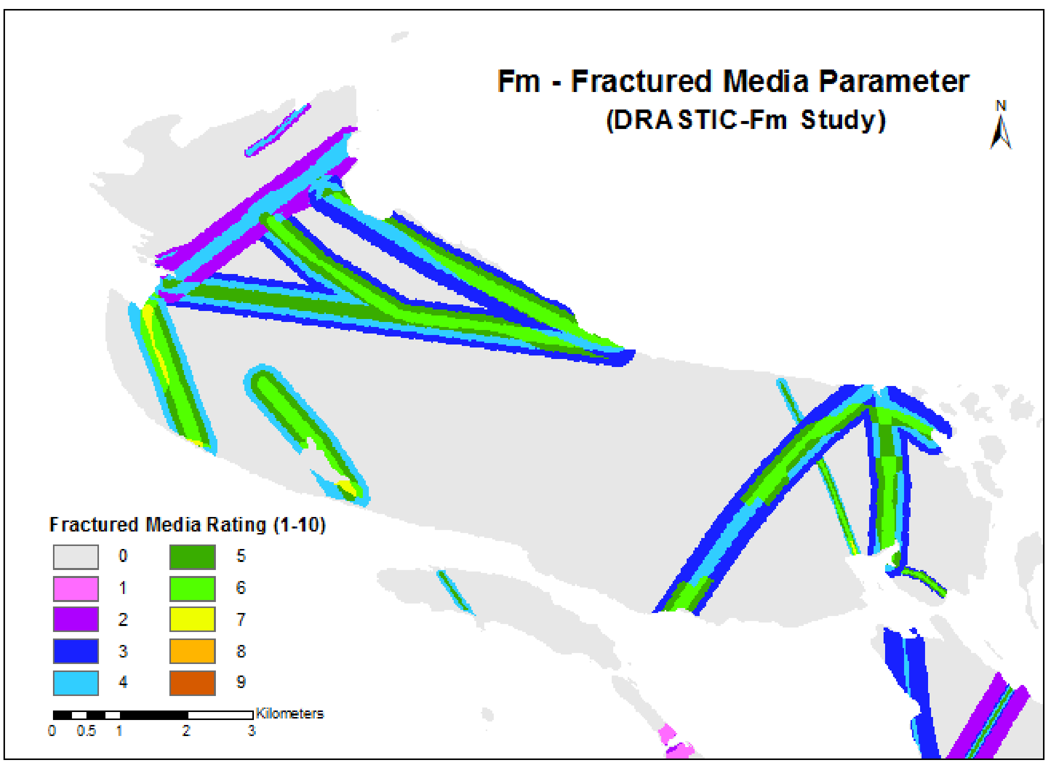


Figure 31 - Original rated raster for Fm parameter, Gabriola Island

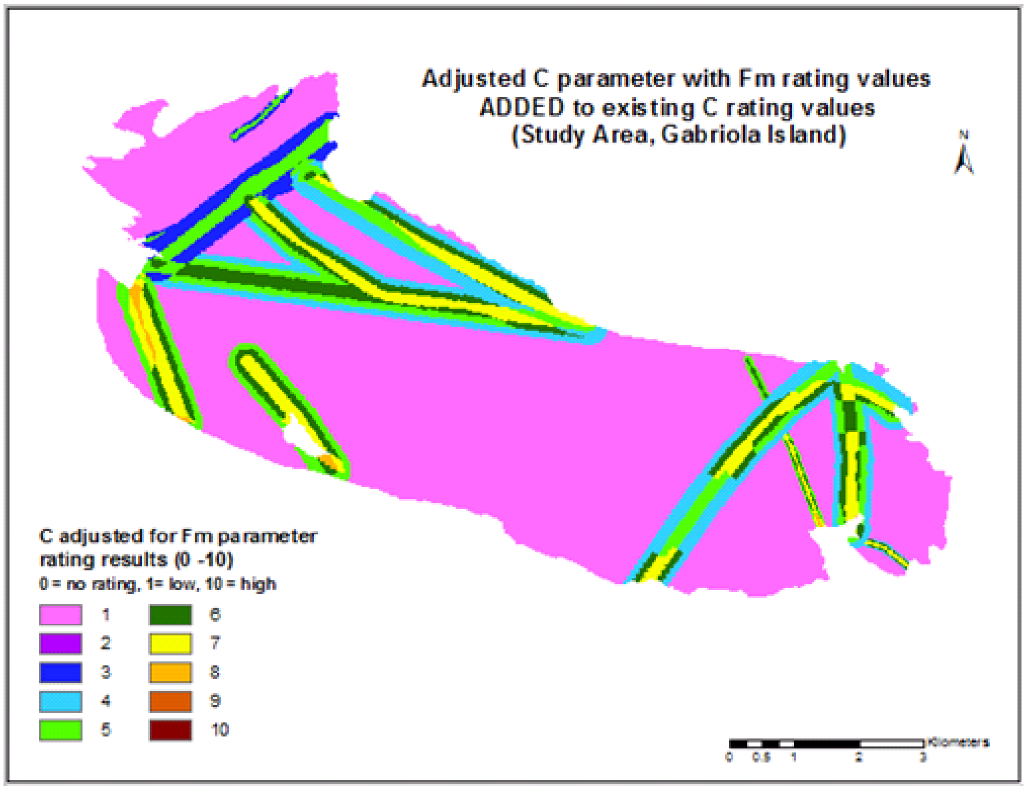


Figure 32 - Reclassified C rated raster with Fm rated values added to existing C values, Gabriola Island

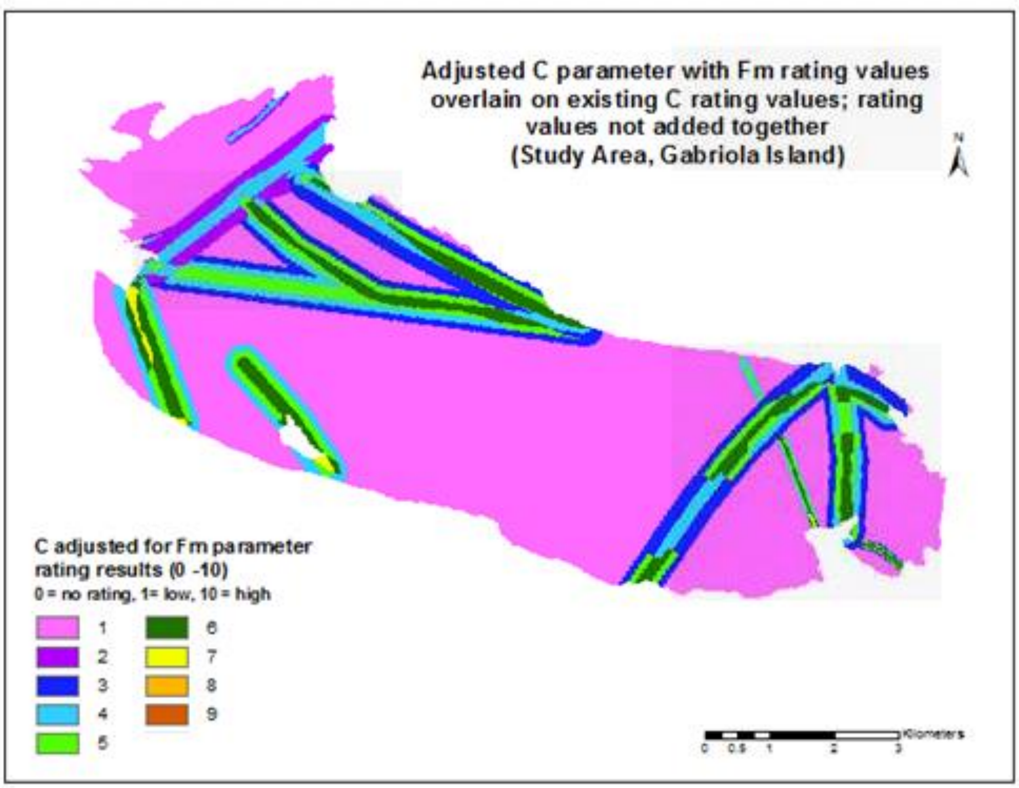


Figure 33 - Reclassified C rated raster with Fm rated values overlain on existing C values, Gabriola Island

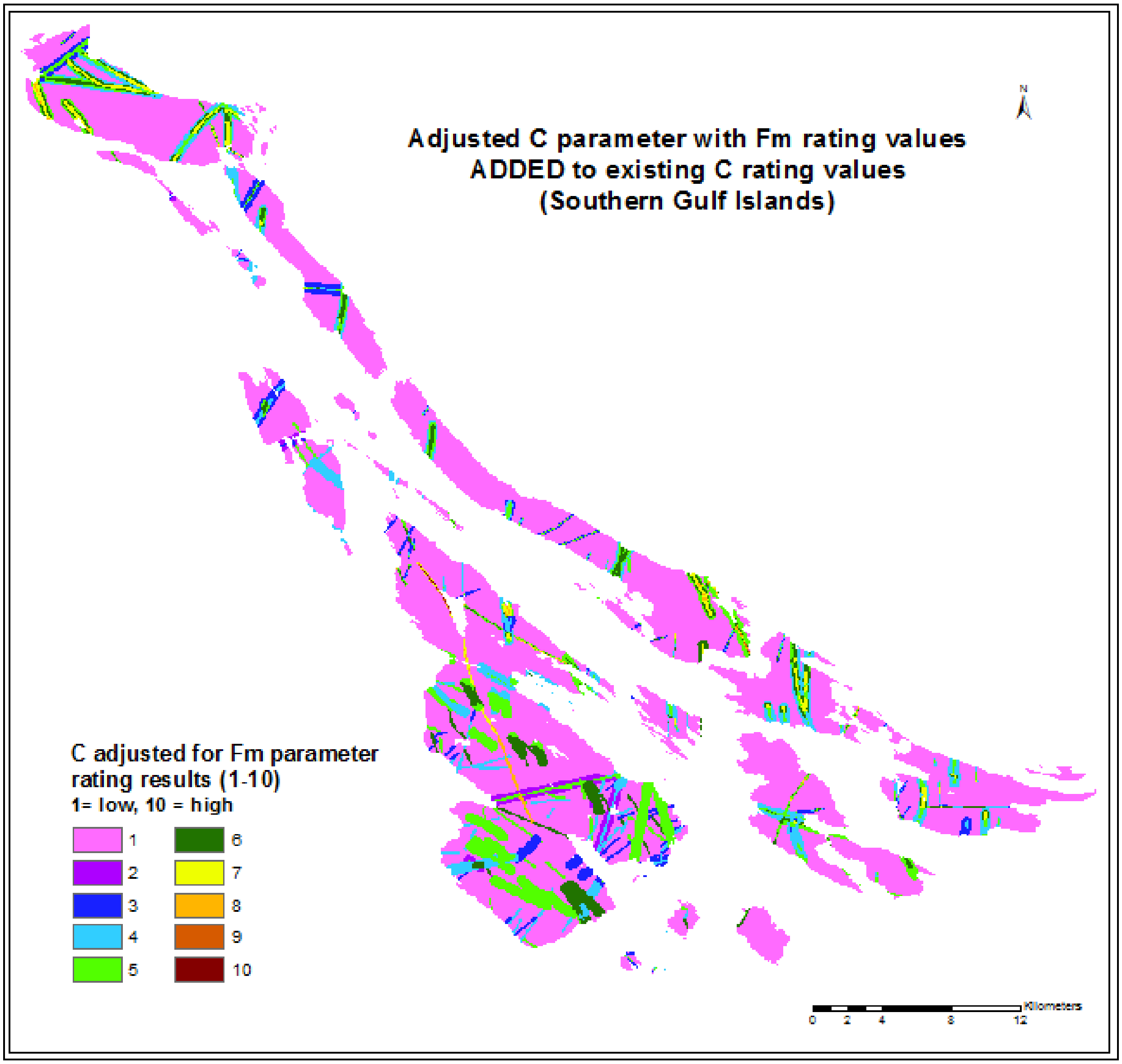


Figure 34 - Reclassified C rated raster with Fm rated values added to existing C values, southern Gulf Islands

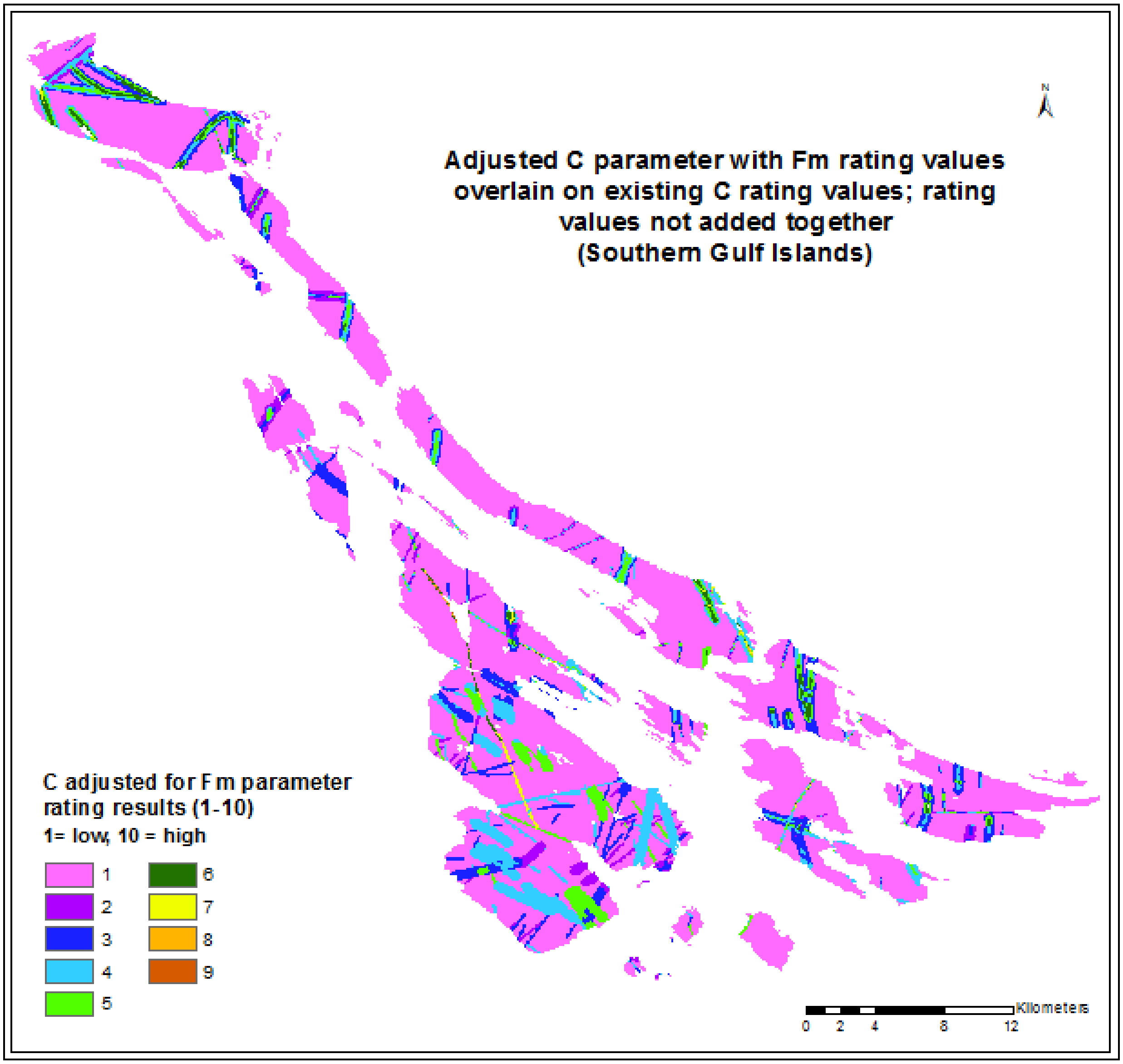


Figure 35 - Reclassified C rated raster with Fm rated values overlain on existing C values, southern Gulf Islands

2.2.2 Relation of C to Other DRASTIC Maps in the Province

The highest rating value for C is between 10 (for add approach) and 9 (for overlain approach). Other DRASTIC maps in BC have generally associated such high C ratings to unconsolidated sediments (e.g., in the Vancouver Island DRASTIC study, Capilano, Salish and Vashon deposits are assigned C ratings of 10 (Newton and Gilchrist, 2010)). Assignment of C rating is based largely on the transmissivity (T) (related to hydraulic conductivity) of the aquifer material. Values of T for the unconsolidated materials comprising the Capilano, Salish and Vashon deposits on Vancouver Island and vicinity range from ~$2x10^{-3}$ to $2x10^{-1}$ m^2/s (Liggett and Gilchrist, 2010). On the Gulf Islands, a synthesis of aquifer test data (Allen et al., 2003) reveals that T values for the sandstones can be as high as $5x10^{-2}$ m^2/s. These high T values tend to be found at locations where the pumping well is in close proximity to a major fracture zone or faults, or is otherwise highly fractured sandstone (Allen, personal communication). The average T value for sandstone on the southern Gulf Islands is $1x10^{-6}$ m^2/s. A Similar, although slightly higher, average T value is obtained for mudstone ($1x10^{-5}$ m^2/s, although based on fewer tests). The maximum T value for mudstone is similar to the average value for mudstone.

The maximum T values estimated in the sandstone formations in the southern Gulf Islands are thought to reflect the highly permeable major fault/fracture zones, which are captured in the Fm parameter (Allen, personal communication). Because the T value can be as high as those corresponding to a C rating of 10, it is reasonable to permit C to attain values of 9 or 10 on the southern Gulf Islands. That is, the adjusted ranges for C (using either method) are consistent with the expected T values of highly fractured bedrock near fault and fracture zones.

2.3 Calculating the Final Intrinsic Susceptibility Range

The two newly created C parameters incorporating Fm with two different approaches were utilized to calculate 2 new intrinsic susceptibility rasters with an overall range of 23-230. These two new sets of IV results were then compared to the original DRASTIC-Fm intrinsic susceptibility results. The equations below demonstrate the calculations utilized.

Final Intrinsic Susceptibility Rating for DRASTIC-Fm:

- Original DRASTIC-Fm:
  (5*D) +(4*R)+(3*A)+(2*S)+(1*T)+(5*I)+(3*C)+(3*Fm) = 'drasfm'
- C with Fm added:
  (5*D) +(4*R)+(3*A)+(2*S)+(1*T)+(5*I)+(3*C) = 'drasfm_Add'
- C with Fm overlain:
  (5*D) +(4*R)+(3*A)+(2*S)+(1*T)+(5*I)+(3*C) = 'drasfm_Over'

The resulting intrinsic susceptibility rasters were masked to the same extent coverage as the original DRASTIC-Fm study. Comparison of the three final rasters minimum and maximum intrinsic susceptibility range is given in Table 3 along with the mean and standard deviation. The addition of Fm rated values to existing C values resulted in intrinsic susceptibility ratings closer to the original rating values than the approach of overlaying Fm on C.

Table 3 - Final Intrinsic Susceptibility results

Final Susceptibility Raster	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
Original DRASTIC-Fm	43	193	117.5270287	42.792783
Adjusted with Fm added to C	43	192	116.527397	42.217018
Adjusted with Fm overlain on C	43	189	115.027972	41.352475

Note: stats on 'value' field.

2.3.1 Map Results

Results portray that *adding* the Fm rated values to the existing C values best captures the fractures of the Fm parameter. By adding Fm values of 1 to areas where C value previously existed as 1 to create a rated value of 2 ensures that even areas of low intrinsic susceptibility from the Fm parameter are not lost. This observation is based on the assumption that intrinsic susceptibility ratings compound with influential additional parameter characteristics. Figures 36-38 visualize the mapped results of this comparison using the rating categories used in the original DRASTIC-Fm study. Zooming in on Gabriola Island, the similarities of the original DRASTIC-Fm results and the addition of Fm to C can be seen in the fractures and rating groupings. The absence of these fractures produced from the Fm parameter characteristics can be seen in the Fm overlay on C map in Figure 38.

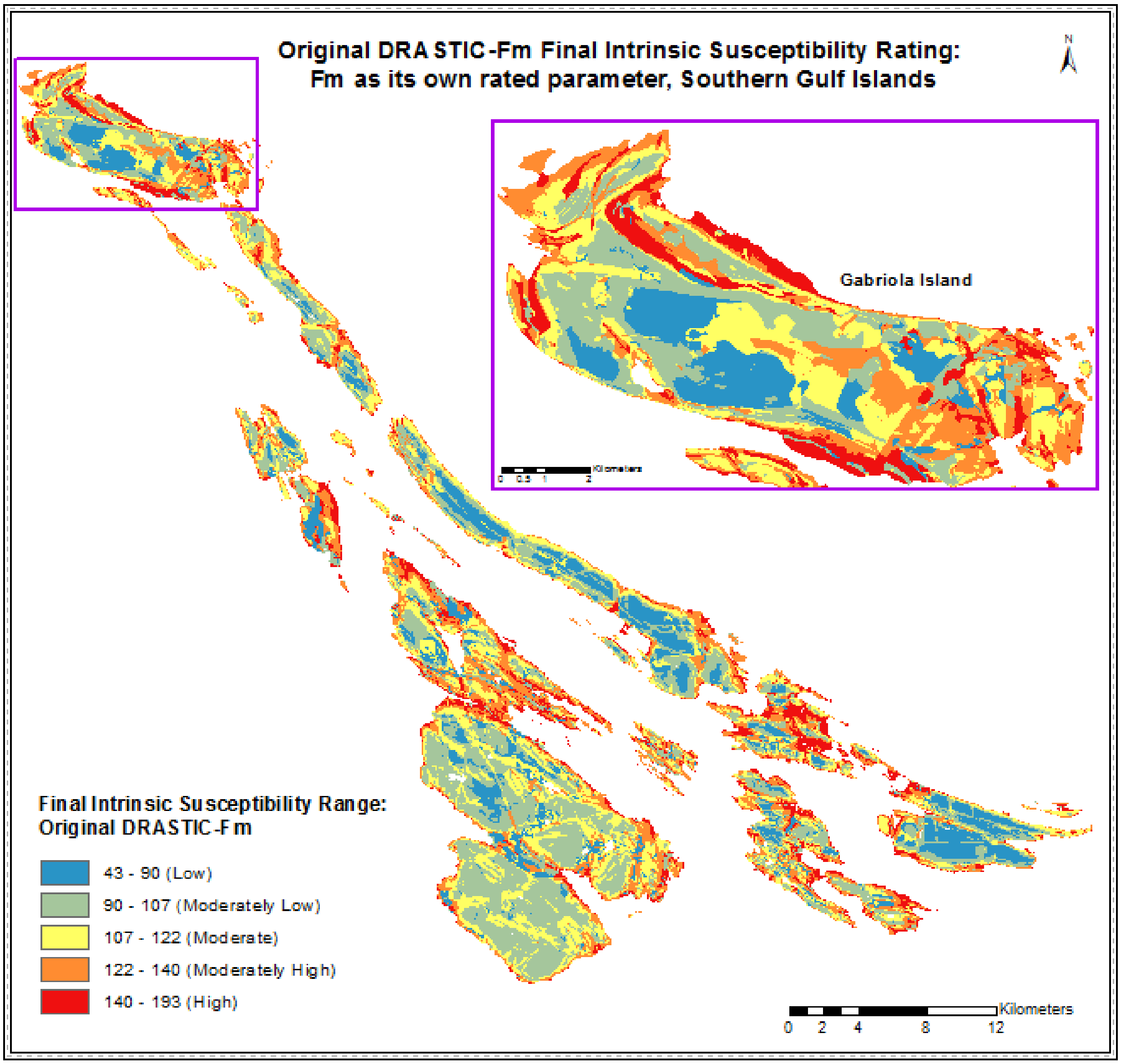


Figure 36 - Original final Intrinsic Susceptibility ratings for DRASTIC-Fm

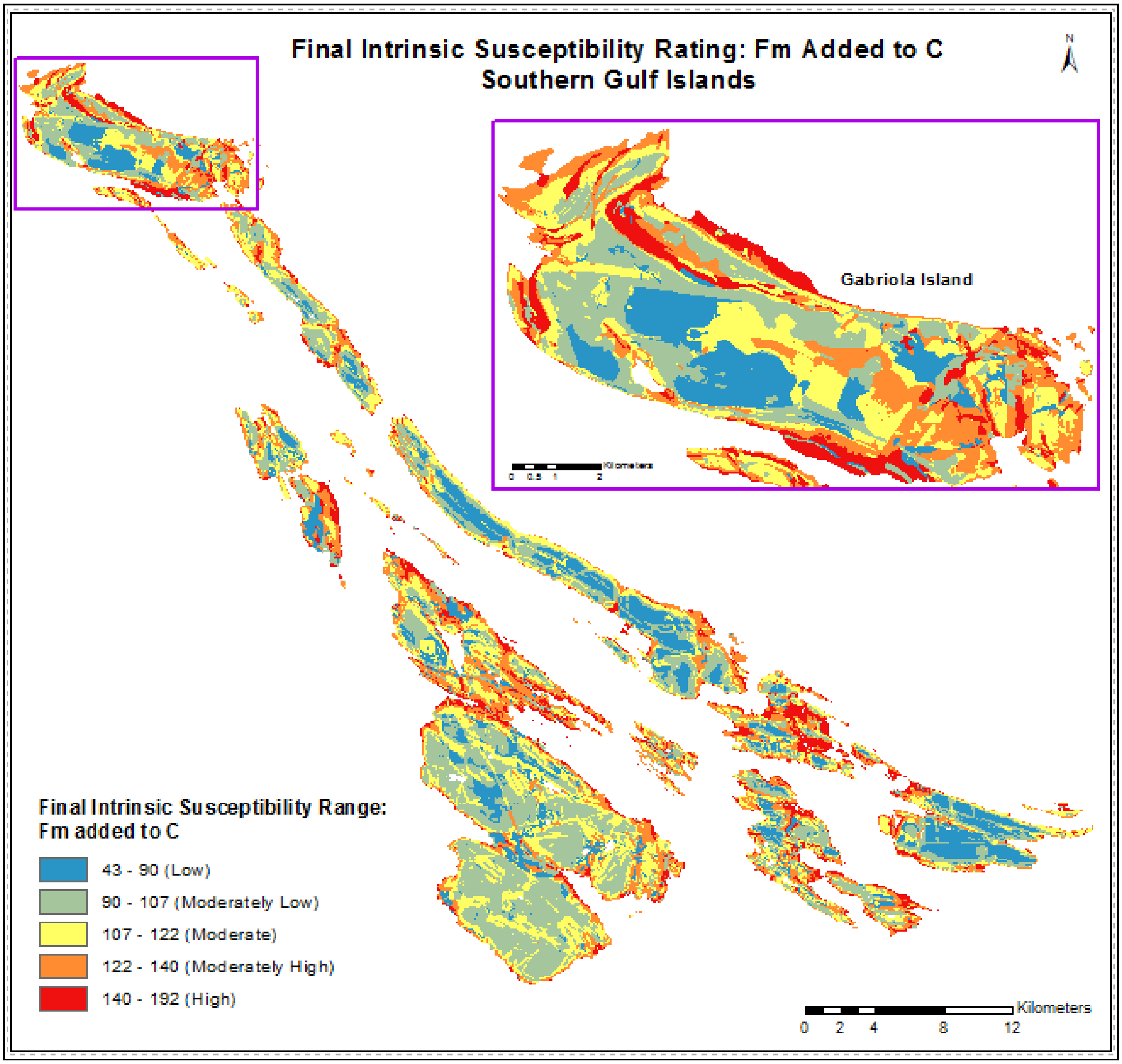


Figure 37 - Final Intrinsic Susceptibility ratings for reclassified C parameter with Fm values added

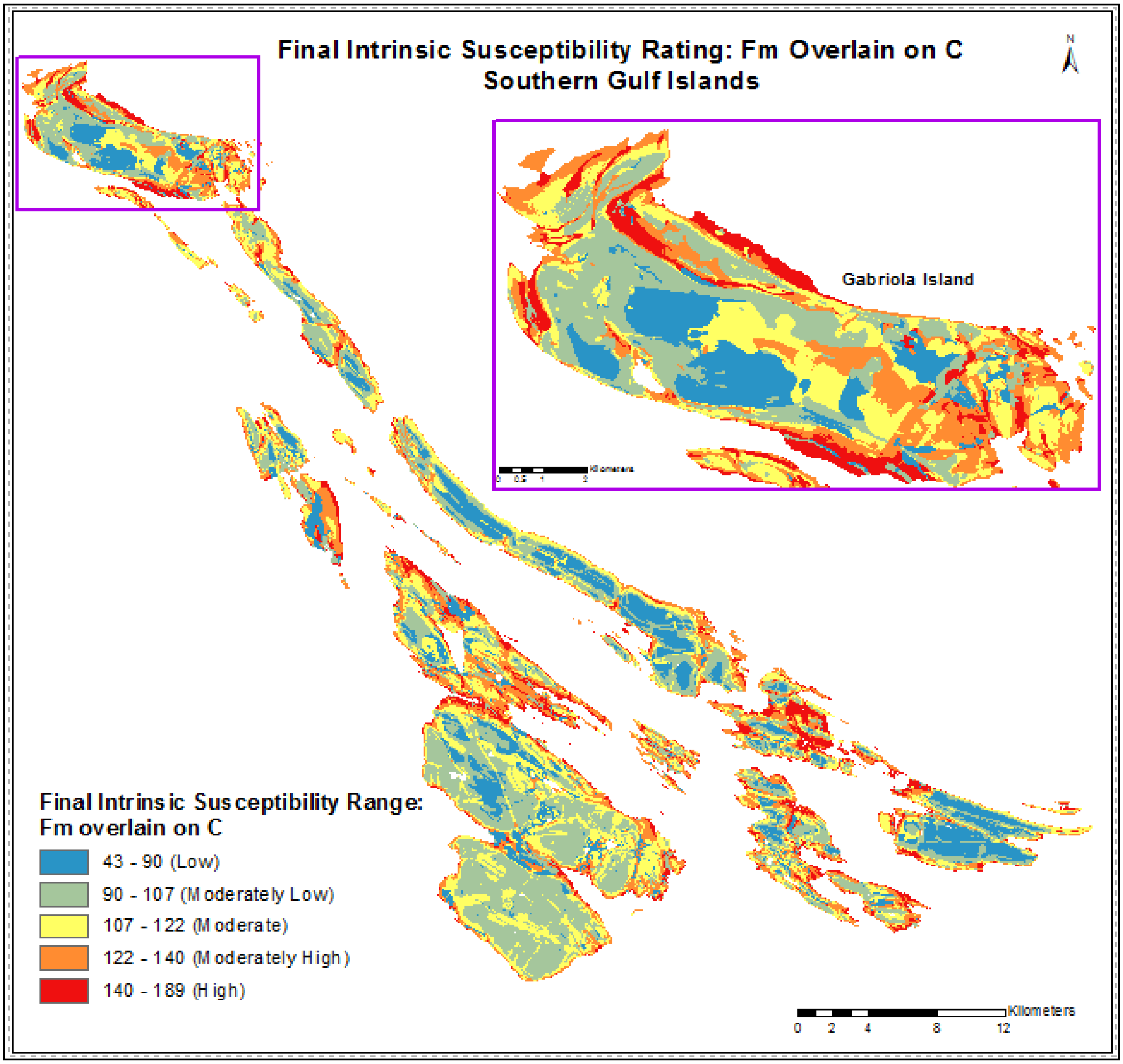


Figure 38 - Final Intrinsic Susceptibility ratings for reclassified C parameter with Fm values overlain

3.0 Project Conclusions

The evaluation of intrinsic aquifer susceptibility to surface pollutants via aquifer susceptibility mapping methods provides a visual and quantitative tool to aid planners and decision makers faced with the growing pressure of development and residential dependency on groundwater as primary source of drinking water. Part 1 of this project utilized GIS-based techniques to compare two studies for the same area (Gabriola Island) that used different approaches to assess intrinsic susceptibility, and thus had different results. The results of this evaluation presents a source for further discussion of these differences, approaches taken and the underlying aquifer characteristics represented.

The results of Part 2 of this project allows for the local application of the DRASTIC-Fm study results, including the influential Fractured Media parameter characteristics, for use in the southern Gulf Islands. The development of an overall DRASTIC-Fm intrinsic susceptibility rating range consistent with the Provincial DRASTIC standard allows for the inclusion of the results in the Provincial mapping database as part of the existing Intrinsic Aquifer Vulnerability (Susceptibility) feature layer accessible to the public via the GeoBC online iMap mapping portal. Figure 39 displays a representation of this final intrinsic vulnerability rating classified using the class ranges defined by the Province.

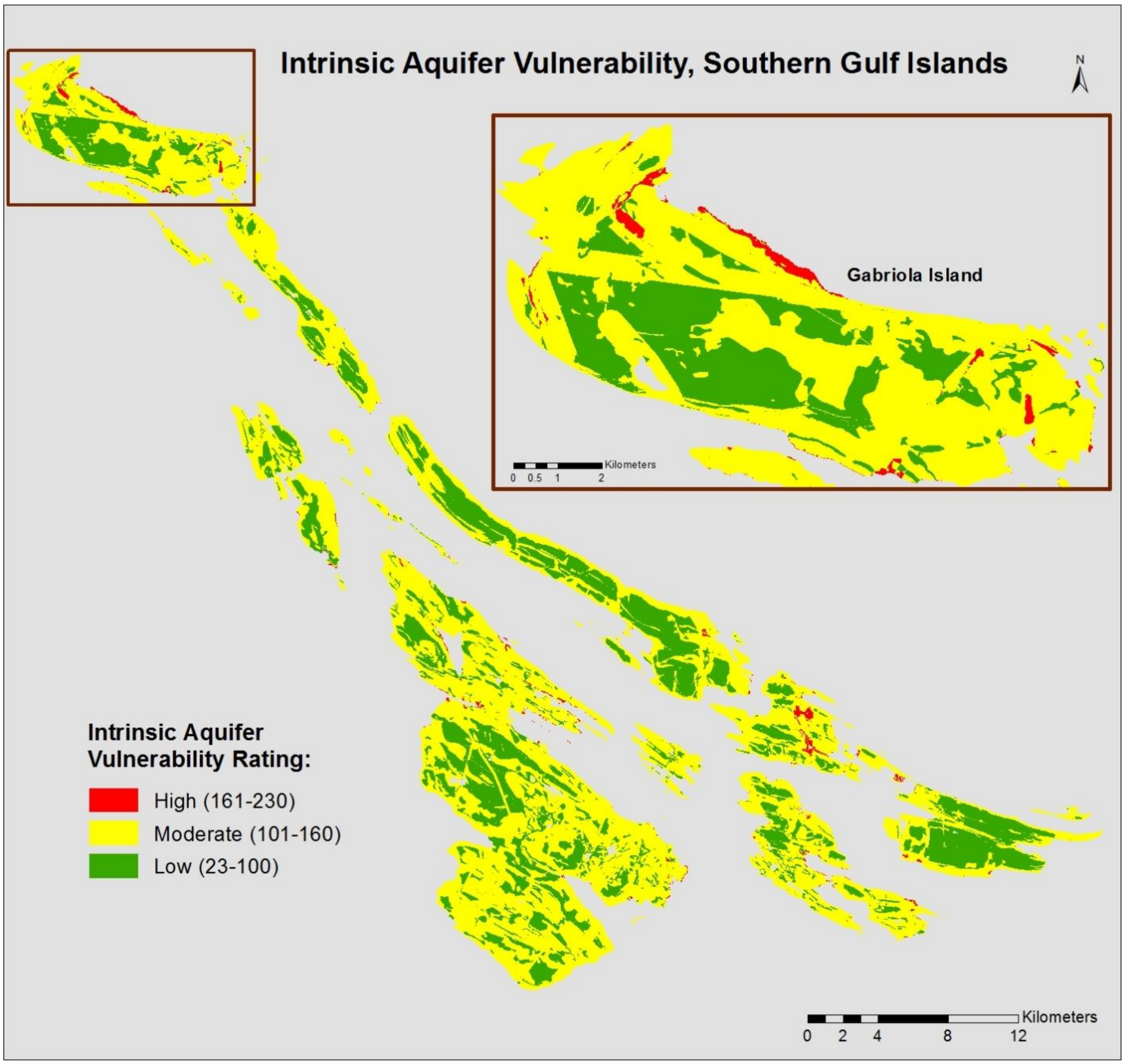


Figure 39 - Intrinsic Aquifer Vulnerability map for the southern Gulf Islands. Vulnerability classes represented based on GeoBC iMap 'Intrinsic Aquifer Vulnerability' layer class values

4.0 References

Allen, D. 2014. DRASTIC-FM Parameter Rating Tables and GIS datasets. Received 4 January 2014.

Allen, D.M., Liteanu, E., Bishop. T.W. and Mackie, D.C. 2003. Determining the Hydraulic Properties of Fractured Bedrock Aquifers of the Gulf Islands, BC. Final Report submitted to Ministry of Water, Land and Air Protection, March 2003, 107pp.

Aller, L., Bennett, T., Lehr, H., Petty, R.J., Hackett, G. 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings, Dublin, Ohio, USA.

Denny, S.C., Allen, D.M., and Journeay, J.M. 2007. DRASTIC-Fm: a modified vulnerability mapping method for structurally controlled aquifers in southern Gulf Islands, British Columbia, Canada.

Liggett, J., 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 p. http://web.viu.ca/gilchrisa/PDF/OF6168_VI%20Technical%20Summary_2010.pdf.

Newton, P., Gilchrist, A. 2010. Technical summary of intrinsic vulnerability mapping methods for Vancouver Island. Vancouver Island Water Resources Vulnerability Mapping Project – Phase 2. Vancouver Island University, Nanaimo, BC. http://web.viu.ca/gilchrisa/PDF/VMP_ Phase2Report _2010.pdf.

5.0 Appendix A

Appendix A lists the rating tables and a brief data description for each of the two discussed studies according to each of the 7 parameters utilized in DRASTIC. Rating tables used in DRASTIC-Fm study were received from Diana Allen (Simon Fraser University) in January 2014. Rating tables used in the Vancouver Island DRASTIC study were acquired from the pilot technical summary paper outlining this study (Liggett and Gilchrist, 2010). Table A1 lists the data sources and respective parameters derived from the listed data for the Vancouver Island DRASTIC study completed in 2010 (Newton and Gilchrist, 2010).

Table A1 - Data sources and respective parameter derivation for the 2010 Vancouver Island study (Newton and Gilchrist, 2010, p. 4)

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

Depth to Water (D)

Table A2 - DRASTIC-Fm D parameter rating table and data information (Allen, 2014)

DEPTH TO AQUIFER

D_original_input (vector file)

A point dataset was created from combining depth to water data from the BC ministry water well database with DEM height values. The point dataset was interpolated to a raster using Inverse Distance Weighted.

D_final_0831 (raster file)

Final D parameter that contains associated index rating.

Depth to Water (D) Index Table

Depth to water (ft)	DRating
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1

Table A3 - Vancouver Island DRASTIC study D parameter rating table (Liggett and Gilchrist, 2010, p. 26)

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

Recharge (R)

Table A4 - DRASTIC-Fm R parameter rating table and data information (Allen, 2014)

RECHARGE

R-value_rating (vector file)

Recharge rates (inches/year) were calculated for soil media in the Gulf Islands using the US EPA model HELP (UnSat Suite, Waterloo Hydrogeologic Inc.). These rates were assigned to soil polygons. Recharge rate fieldname: inches_yea, rating fieldname: R

R_final_0831 (raster file)

Final R parameter that contains associated index rating.

Recharge (R) Index Table

Inches/year	R-Rating
0-2	1
2-4	3
4-7	6
7-10	8
10+	9

Table A5 - Vancouver Island DRASTIC study R parameter rating table (Liggett and Gilchrist, 2010, p. 28)

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

Aquifer Media (A)

Table A6 - DRASTIC-Fm A parameter rating table and data information (Allen, 2014)

AQUIFER MEDIA

Sand polygons included:

C_A_geology(vector file)

Aquifer media ratings were assigned based on geological formation characteristics. A rating fieldname: A

A_final_0831 (raster file)

Final A parameter that contains associated index rating.

Sand Polygons excluded:

Geology_gi_clip_join (vector file)

Aquifer media ratings were assigned based on geological formation characteristics. A rating fieldname: A

Afinalnosand (raster file)

Final A parameter that contains associated index rating.

Aquifer media (A) Index Table

Geological Formation	**A**
Cedar District	5
Comox	6
De Courcy	6
Pender	1
Extension	1
Gabriola	1
Geoffrey	6
Haslam	5
Northumberland	5
Protection	1
Spray	5
Buttle lake	3
Mount Hall	3
Sicker group	3
Salt Spring intrusion	3
Sand and Gravel	8

Table A7 - Vancouver Island DRASTIC study A parameter rating table (Liggett and Gilchrist, 2010, p. 31-32)

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

Soil Media (S)

Table A8 - DRASTIC-Fm S parameter rating table and data information (Allen, 2014)

SOIL MEDIA

S_T_soil *(Vector File) S_lookup (lookup table)*

Soil ratings were assigned based on soil properties. The associated lookup table corresponds to the soil dataset (S_T_Soil)

S_final_0831 (raster file)

Final S parameter that contains associated index rating.

Soil Media (S) Index Table

DOMSOIL	S	SOIL_NAME
BD	8	BEDDIS
BE	2	BRIGANTINE
BH	8	BELLHOUSE
BY	3	BAYNES
CF	1	CROFTON
CO	1	COWICHAN
FB	2	FAIRBRIDGE
GA	6	GALIANO
HA	6	HASLAM
ME	5	MEXICANA
MG	7	MUSGRAVE
MT	1	METCHOSIN
NT	7	NEPTUNE
PA	1	PARKSVILLE
QU	8	QUALICUM
PD	8	PENDER ISLAND
RO	10	ROCK
RY	7	RUMSLEY
SL	8	SALALAKIM
SM	3	ST. MARY
ST	7	SATURNA
SU	2	SUFFOLK
TL	1	TOLMIE
TR	4	TRINCOMALI
CB	10	COASTAL BEACH
MD	5	MADE LAND
TF	3	TIDAL FLAT
W	0	WATER
DA	3	DENMAN ISLAND
CH	2	CHEMAINUS

Table A9 - Vancouver Island DRASTIC study S parameter rating table (Liggett and Gilchrist, 2010, p. 34-35)

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

Topography (T)

Table A10 - DRASTIC-Fm T parameter rating table and data information (Allen, 2014)

TOPOGRAPHY

S_T_soil *(Vector File)* T_lookup *(lookup table)*

Topography ratings were assigned based on slope percent values contained within the soil dataset polygons. The associated lookup table corresponds to the soil dataset (*T_lookup*)

T_final_0831 (raster file)

Final T parameter that contains associated index rating.

Topography (T) Index Table

SLOPE_PERC	SLOPE_DEGS	SLOPE1	T
0-0.5	0	1	10
0.5-2	0-3.1	2	10
2.0-5.0	1.0-3.0	3	9
6.0-9.0	3.5-5.0	4	5
10.0-15.0	6.0-8.5	5	3
16-30	9.0-17.0	6	2
31-45	17.0-24.0	7	1
46-70	25.0-35.0	8	1
71-100	35.0-45.0	9	1
>100	>45	10	1

Table A11 - Vancouver Island DRASTIC study T parameter rating table (Liggett and Gilchrist, 2010, p. 37)

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

Impact of Vadose Zone (I)

Table A12 - DRASTIC-Fm I parameter rating table and data information (Allen, 2014)

IMPACT OF VADOSE ZONE

I_value_rating *(vector file)*

Hydraulic conductivity values were calculated for different lithologies encountered in the Gulf Islands. These hydraulic conductivity values were applied to soil polygons and associated ratings were assigned. Hydraulic conductivity fieldname: KZ_I, Rating fieldname: I.

I_final_0831 *(raster file)*

Final I parameter that contains associated index rating.

Impact of Vadose Zone Media (I) Index Table

Equivalent lithological description	KZ_I	IRating
till, hardpan, clay	<-5	1
	-4	2
sandy till, clayey silt, bedrock	-3	3
	-2	4
silt, sandy silt	-1	5
fine sand, silty sand	0	6
medium sand, sand	1	7
sand and gravel, coarse sand	2	8
gravel	>3	9
no vadose zone		10

Table A13 - Vancouver Island DRASTIC study I parameter rating table. Note: parameter A and I have the same rating table (Liggett and Gilchrist, 2010, p. 31-32)

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

Hydraulic Conductivity (C)

Table A14 - DRASTIC-Fm S parameter rating table and data information (Allen, 2014)

AQUIFER CONDUCTIVITY

Sand polygons included:

C_A_geology (vector file)

Aquifer conductivity ratings were assigned based on geological formation characteristics. C rating fieldname: C

C_final_0831 *(raster file)*

Final parameter that contains associated index rating.

Sand Polygons excluded:

Geology_gi_clip_join (vector file)

Aquifer conductivity ratings were assigned based on geological formation characteristics. C rating fieldname: C

Cfinalnosand (raster file)

Final parameter that contains associated index rating.

Conductivity (C) Index Table

Aquifer material	Conductivity Range (m/s)	CRating
Clay, silt, Clay and glacial, clay and boulder, glacial, clay and organic, clay and sand, sandstone and (clay, glacial, hale, etc), granite, sandstone, metamorphic rocks, Other volcanic rocks, overburden	less than 5E-6	1
Gravel and clay, Limestone, sand and silt	5e-6 to 5e-5	2
Sand	5e-5 to 5e-4	4
Basalt, gravel, gravel and boulder, sand and gravel	greater than 1e-3	10

Table A15 - Vancouver Island DRASTIC study C parameter rating table (Liggett and Gilchrist, 2010, p. 43-45)

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

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
$4.0x10^{-2} – 4.1x10^{0}$	Bedrock – all types (B), clay (T), silty clay (T), gravelly silty clay (T), sandy clay (T), clayey silt (T)	1
$4.2x10^{0} – 1.2x10^{1}$	Silt (T), sandy silt (T)	2
$1.3x10^{1} – 2.9x10^{1}$	morainal (T)	4
$3.0x10^{1} – 4.1x10^{1}$	Quadra Sand (W)	6
$4.2x10^{1} – 8.2x10^{1}$	Alluvium (T), organics (T), undifferentiated (T), silty sand (T), colluvium (T), fluvial (T), mixed fragments (T)	8
$>8.2x10^{1}$	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

Fractured Media (FM)

Table A16 - DRASTIC-Fm FM parameter rating table and data information (Allen, 2014)

FRACTURED MEDIA

FM_azimuth_length & FM_fracture_intensity *(vector files)*

Two vector files represent the FM parameter. The FM_azimuth_length file represents the polyline portion of the fm parameter which contains azimuth and length values. The FM_fracture_intensity file represents the polygon portion of the fm parameter which contains line buffers representing different fracture intensities based on geological formation.

FM_all_final_rating *(raster file)*

The two vector files were combined into one raster file, this raster file represents the final FM parameter and includes associated ratings.

Fractured Media (FM) Index Tables

Orientation/Azimuth			
Contractional	Min	Max	Rating
	285	315	7
	315	345	10
	345	15	7
	105	135	7
	135	165	10
	165	195	7
Extensional	195	225	4
	225	255	2
	255	285	4
	15	45	4
	45	75	2
	75	105	4

Length (m)	Rating
20000 - 25000	10
15000 - 20000	8
10000 - 15000	6
5000 - 10000	4
0 - 5000	2

FRAC_INTEN	RATING
0-2	2
2-4	4
4-6	6
6-8	8
>8	10

DRASTIC Parameter Weighting Scheme

Table A17 - DRASTIC intrinsic aquifer susceptibility parameter rating scheme used in both DRASTIC studies (Allen, 2014)

Hydrogeologic Factor	Weight
D – Depth to Water	5
R – Net Recharge	4
A – Aquifer Media	3
S - Soil Media	2
T - Topography	1
I – Impact of Vadose Zone Media	5
C – Aquifer Hydraulic Conductivity	3
FM – Fractured Media	3

Differences in Cell Count

Table A18 - Cell count values per parameter rating values by DRASTIC parameter for Vancouver Island DRASTIC and DRASTIC-Fm studies

	D		R		A		S		T		I		C	
VALUE	VI	Fm	VI	Fm	VI	Fm	VI	Fm	VI	Fm	VI	Fm	VI	Fm
1	772	299	0	0	0	0	47	315	515	243	0	32	5308	5233
2	494	941	0	0	0	0	442	70	0	99	0	507	0	0
3	812	1294	0	309	0	0	316	10	336	122	0	309	0	0
4	0	0	0	0	3702	0	0	0	0	773	0	40	0	0
5	976	1037	0	3129	1356	3843	649	0	1584	2060	3843	3196	0	0
6	0	0	5239	0	124	1465	0	74	0	0	1400	845	0	0
7	887	995	0	0	51	0	0	3104	0	890	0	6	0	0
8	0	0	0	0	0	0	3203	853	0	0	0	9	0	0
9	498	490	0	0	0	0	251	0	2292	862	0	299	0	0
10	867	197	0	1801	0	0	312	795	518	196	0	0	0	0
TOTAL CELLS	5306	5253	5239	5239	5233	5308	5220	5221	5245	5245	5243	5243	5308	5233