QUANTIFYING RECHARGE TO FRACTURED AQUIFERS USING A DISCRETE FRACTURE NETWORK APPROACH
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ABSTRACT
This study applies the concept of hydrostructural domains to a dataset comprising approximately 9000 fractures measured at 157 stations in the Gulf Islands, BC, Canada. Discrete fracture network models that statistically honour field data were constructed for representative stations of each of three hydraulically distinct domains including, “highly” fractured interbedded sandstone and mudstone (<10.0 cm spacing), “less” fractured sandstone (>1.0 m spacing), and fault and fracture zones. Vertical permeability was determined for each domain by modeling flow through a volume using an EPM approach. Recharge was mapped using GIS linked to HELP (USEPA). The recharge model accounts for soil permeability and depth, vadose zone depth, slope, and permeability of the vadose zone aquifer media (as determined from the fracture modeling). Recharge is driven by physically-based daily weather inputs generated by a stochastic weather generator that is calibrated to local observed climate, and the spatial and temporal (monthly) variations in recharge are mapped. Recharge ranges from 184 to 537 mm/year (or an average of 14 to 41 mm/month), although mean monthly recharge varies considerably throughout the year.

RÉSUMÉ
Cette étude applique le concept des domaines hydro-structurels à un jeu de données acquises à 157 stations dans la région de Gulf Islands (CB, Canada) comprenant approximativement 9000 fractures. Le réseau discret de fracture montre une concordance statistique tout à fait acceptable avec les données de terrain, établies pour des stations représentatives de chacun des trois domaines hydrauliques distincts, incluant des grès et argiles intercalés hautement fracturés (espacement <10.0 cm), des grès moins fracturés (espacement >1.0 m), et des failles et zones fracturées. La perméabilité verticale a été déterminée pour chaque domaine en modélisant l’écoulement à travers un volume et en utilisant une approche EPM. La recharge a été intégrée en utilisant le système GIS couplé au logiciel HELP (de USEPA). Le modèle de recharge prend en compte la profondeur du sol et sa perméabilité, la profondeur de la zone vadose et sa perméabilité (déterminée par le modèle de fracture), et la pente. La recharge est calculée par un modèle stochastique, générant les conditions météorologiques journalières, et qui est calibré à partir d’observations climatiques locales. Les variations spatiales et temporelles (mensuelles) de la recharge peuvent ainsi être cartographiées. La valeur de la recharge est comprise entre 184 et 537 mm/an (soit une moyenne de 14 à 41 mm/mois), bien que la recharge moyenne mensuelle varie considérablement au cours de l’année.

1. INTRODUCTION
Quantifying groundwater recharge to fractured rock aquifers presents significant challenges, particularly for application to regional scale watersheds. At a regional scale, variations in the intensity of fracturing invariably lead to heterogeneous fracture distributions, which are difficult to represent spatially, and equally difficult to quantify in terms of relative permeability.

In this study, we employ a hydrostructural domain approach proposed by Mackie (2002) to quantify the permeability of an aquifer system that is variably fractured. Hydrostructural domains are defined on the basis of changes in fracture intensity and, thus, characterize the distribution of relative permeability/hydraulic conductivity. The K values are used to represent the fractured vadose zone in a one dimensional water balance recharge model. Spatially-distributed and temporally-varying recharge is mapped for the Gulf Islands, British Columbia (BC), Canada.

2. PHYSIOGRAPHY AND HYDROGEOLOGY
The southern Gulf Islands (359 km² in area) are situated to the southeast of Vancouver Island, within the Strait of Georgia, BC (Figure 1). The topography is controlled primarily by northwest-southeast trending ridges up to 450 masl and valleys formed by accelerated weathering of less competent mudstone lithologic units. The Islands support a growing population that is dependent on groundwater as its primary source of drinking water, similar to many other populated island systems worldwide. High water usage during the summer holiday season, low recharge to aquifers during the summer and early fall, and increasing residential development along the coast complicates groundwater management in the Gulf Islands.

Groundwater for domestic supply is derived from the fractured sedimentary rocks of the Late Cretaceous Nanaimo Group (~91-66 Ma) (Mustard 1994). The strata are primarily alternating sequences of sandstone-
dominant and mudstone-dominant formations. The contacts between the formations are typically transitional, and are usually characterized by the presence of interbeds. The sedimentary rocks of the Nanaimo Group have undergone three major deformation events in response to past tectonic stress (Journeay and Morrison 1999). The first event resulted in a southwest vergent thrust system defined by northwest trending, northeast dipping thrust faults and asymmetric folds (Journeay and Morrison 1999). The features resulting from a second southeast vergent thrust system include northwest trending buckle folds and associated northeast vergent thrust faults (Journeay and Morrison 1999). Shallow dipping features, representing bedding plane partings, suggest formation during uplift and/or isostatic rebound after deglaciation (Mackie 2002). Locally, numerous younger northeast trending fault and fracture zones as well as bedding perpendicular joints are present (Mustard 1994; Mackie 2002).

Figure 1: Location map and regional setting of Mayne Island (48°52'N, 123°18'W) and surrounding southern Gulf Islands in southwestern British Columbia, Canada.

Previous hydrogeological investigations suggest that primary porosity is low and of minor importance in the storage and transport of groundwater (Dakin et al. 1983). Permeability is thought to be derived primarily from fractured intervals found in conjunction with mudstone-dominant formations or interbedded contact zones (Abbey 2000; Allen and Suchy 2001). Drill logs also show that principal water bearing aquifers within the Nanaimo Group rocks are the highly fractured mudstone-dominant units as well as the geologic contacts (Allen and Suchy 2001). The unconsolidated surficial deposits on the islands consist of Pleistocene glacial-marine sediments generally less than 18 m thick (Clague 1994). Because of these deposits are typically present only as a thin veneer, they do not offer a significant source of groundwater.

3. FRACTURE COLLECTION AND ANALYSIS

3.1 Field Data Collection

Previously-collected fracture data indicate that the Gulf Islands can be divided into three hydraulically distinct hydrostructural domains (Mackie 2002). These domains are, in part, lithology-dependent and reflect changes in fracture intensity within the rock mass. The three domains represent: 1) “highly” fractured interbedded mudstone and sandstone (with fracture spacing < 10 cm) (IBMS-SS), 2) “less” fractured sandstone (with fracture spacing > 1 m) (LFSS), and 3) fault and fracture zones (FZ) (Figure 2). Permeability is thought to increase closer to fault and fracture zones, and within the highly fractured interbedded mudstone and sandstone domain.

Figure 2: Hydrostructural domain conceptual model for Mayne Island showing in order of increasing relative permeability: LFSS, IBMS-SS, FZ domains (modified from Mackie, 2002).

Using this hydrostructural domain model, representative exposures for each of the domains were sampled during the summer of 2004. Although all of the southern Gulf Islands were sampled (Surrette in prep); however, in this paper we focus on the results for Mayne Island. A total of 8 outcrops from Mackie (2002) were re-sampled to provide fracture trace length and aperture estimates. These estimates were not originally recorded and are integral in defining flow along a fracture. The fracture data were collected using scanline sampling. This technique uses a graduated tape-measure stretched across an outcrop face at near right angles to major fracture sets. This orientation avoids scanline-fracture set orientation bias (Caine and Tomusiak 2003). Exposures with at least two near-orthogonal faces were targeted to capture fractures sub-parallel to one of the outcrop faces. This method further reduces scanline orientation bias (Terzaghi 1965; Baecher 1983).


3.2 Statistical Analysis

To ensure that the re-sampled fracture data were statistically representative of the data collected by Mackie (2002), a Watson-Williams' test of means for spherical data was run. This test determines the equivalency of the mean fracture orientations from two sets of observations (Mardia 1972). The test results showed that the re-sampled fracture populations used in this study were not statistically different from the previously sampled populations (95% confidence interval).

Further comparison of fracture measurements from the three hydrostructural domains using the Watson-Williams test-of-means identified five statistically different groups. These groupings show that fractures within the same domain tend to have similar fracture characteristics and these characteristics are statistically different from those in other hydrostructural domains. However, this classification does not strictly hold true for a hydrostructural domain that has undergone a different deformational history. For example, the different deformational histories of this study region (as described earlier) results in two sub-groups within each of the LFSS and the FZ domains. The LFSS domain consists of one group that is statistically representative of the domain, and another group that is in closer proximity to a fault zone. This proximity results in statistically different fracture orientations even though this second group is classified as being in the LFSS domain. Similarly, the FZ domain contains two fault zones, each with statistically different orientations (northeast and northwest) and, therefore, two different fracture groups. Only one fracture group was identified within the IBM-SS hydrostructural domain.

The fracture orientation data for the statistically different groups were plotted on an equal-area Schimdt nets. Individual sets of fractures were identified using an arbitrary origin cluster analysis (Davis 2002). The mean direction and dispersion factor for each fracture set was then determined for each identified cluster. These results were used as an initial approximation in the simulation of the best-fit probability density functions for the orientation and trace length data.

3.3 Stochastic Modeling

The FracSys module of the FracMan package was used in a statistical analysis of the fracture data (Dershowitz et al. 1998). FracSys uses a forward modeling approach to determine the statistical distributions for fracture orientation and trace length that are a 'best-fit' of the field data. A simulated set of field data is produced from an initial input approximation of the statistical descriptions (determined through cluster analysis) and compared to actual field measurements. The assumed statistical distribution is modified until the goodness-of-fit between the measured and simulated field observations is statistically significant. Significance is determined by a Kolomogorov-Smirnov (K-S) test. A confidence level of 90% was sought although not always achieved, as some data were difficult to fit at this level.

Stochastic model results for the five statistically different groups indicate that fracture set orientation is typically best-fit with a Fisher or a Bivariate Bingham probability distribution function (Dershowitz et al. 1998; Davis 2002). The majority of the fracture trace length data used in this paper are log-normally distributed although some of the data are better approximated by exponential, power law and constant distributions. These statistical models for fracture orientation and trace length are used directly in the construction of discrete fracture network (DFN) models.

3.4 Discrete Fracture Networks

Discrete fracture network (DFN) models were constructed for each station location on Mayne Island using FracWorks XP (Dershowitz et al. 2004). Each DFN model domain was constructed as a 20m by 20m by 20m cube, and populated with fractures according to the orientation and trace length probability distributions derived from the stochastic modeling. The simulated fractures were modeled as smooth, parallel-walled, hexagonal fractures with no elongation (aspect ratio of one). Fracture spacing was described by an enhanced Baecher model (Dershowitz et al. 1998) following a Poisson process. This model was used, as field observations suggested that the fractures were randomly distributed with no clear tendency towards clustering. Fracture set termination percentages calculated from field observations are honoured in the DFN models.

A constant fracture aperture of 100µm (0.0001m) was assumed for all fractures even though applying a constant fracture aperture is not thought to accurately represent natural fractures (Liu 2005; Neuman 2005). An aperture of 100µm is within the range of fracture apertures measured in the field from surface outcrops. However, the measured apertures are likely not representative of fracture apertures at depth. The significance of the assumption of a constant aperture was addressed through a sensitivity analysis (Surrette in prep).

Transmissivity values for individual fractures, typically acquired through packer testing, were not available for this study as domestic wells were inaccessible. Therefore, a constant transmissivity value was assigned to each fracture in the DFN model. The fracture transmissivity was calculated using the cubic law, which is related to the cube of the fracture aperture (e.g., Snow 1968). This resulted in a fracture transmissivity value of $6.24 \times 10^{-08}$ m$^2$/s, being applied to each simulated fracture.

The number of fractures per unit scanline length or fracture intensity is converted to volumetric fracture intensity in FracWorks XP. This conversion results in a fracture surface area per unit volume. The first step in the calculation of volumetric fracture intensity and, ultimately, the calibration of the model to field data, is to generate a simulated scanline using the FracMan code SamEdit XP. The simulated scanline maintains the same orientation (trend/plunge) as measured in the field, thus removing the need to correct for fractures not perpendicular to the
scanline, while maintaining the same fracture spacing distribution. The model fracture intensity is compared to field values, and the fracture set is regenerated until the simulated fracture intensity matches the observed fracture set intensity.

Ultimately, the best-fit DFN models are used in the calculation of the hydraulic conductivity tensor within a geocellular grid. StrataFrac XP works in conjunction with FracWorks XP to link the discrete fracture networks to geocellular grids, such as MODFLOW. The geocellular grid used for this study was 0.2m by 0.2m by 0.2m, which equates to one million grid cells. The assignment of hydraulic properties to the grid nodes is carried out using the Oda Analysis process (Oda 1984). This process calculates the hydraulic conductivity tensor from the fracture network properties. Unfortunately, the StrataFrac output file containing the hydraulic conductivity tensor for each model cell was not compatible with the MODFLOW platform GMS (Groundwater Modeling System), the continuum modeling software used in this study. As a result, a custom code was written to transform the StrataFrac output file into a format that GMS recognizes (M. Toews pers. comm. 2005).

3.5 Parameter Estimation

Potential fracture network permeability represents the fracture network connectivity for each DFN model. Estimates of potential permeability require flow simulations through the fracture networks. Groundwater flow was simulated using a hybrid DFN-EPM modeling approach using the MODFLOW platform GMS. Boundary conditions were assigned according to a simple geographic coordinate system: north-south, east-west and top-bottom directions (after Caine and Tomusiak 2003). A uniform hydraulic head gradient of 0.01m/m was applied to the model using specified head boundaries at opposing cube faces. Zero flux conditions were specified on the remaining four model faces. One-dimensional steady-state “directional” flow was simulated. The volumetric fluid flux was then computed along each specified head boundary, and used to calculate the equivalent bulk potential permeability ($k_p$) for each model domain, in each direction. Hydraulic conductivity was then calculated using standard fluid properties. The top-bottom results were used in recharge modeling.

4. VERTICAL PERMEABILITY RESULTS

The model results suggest that the most permeable units on Mayne Island are the IBMS-SS and FZ hydrostructural domains with potential permeability in the order of $10^{-13}$ m². This is an order of magnitude greater than the potential permeability of the LFSS domain ($10^{-14}$ m²). These results are generally consistent with the conceptual model proposed by Mackie (2002), which suggests that the IBMS-SS domains are likely the dominant water transmitting aquifers on Mayne Island, or at least regulate groundwater flow in the shallow subsurface. This dominance is largely due to the presence of sub-horizontal bedding plane partings. However, the hydraulic role of the bedding plane partings diminishes with depth as the sub-horizontal features are affected by increasing vertical stresses (Morin and Savage 2003). High angle fracture zones (FZ), typically associated with the sandstone dominant domains (LFSS), are not influenced by the increasing horizontal stresses, and likely become the dominant pathways for fluid flow at greater depths. Generally, the potential permeability results presented here are supported by drilling and geophysical observations of increased flow in the mudstone dominant domains (IBMS-SS) and at geologic contacts (Allen et al., 2002). The relationship between higher flows and high fracture densities is further supported by the location of high yielding water wells in close proximity to fault zones and geologic contacts throughout the Gulf Islands.

Table 1 shows the results for vertical hydraulic conductivity for each domain calculated from the Mayne Island data. The LFSS domain has the lowest vertical hydraulic conductivity of the three hydrostructural domains. The results for the IBMS-SS and FZ domains give similar, and higher, estimates.

Table 1: Vertical hydraulic conductivities for the three domain types on Mayne Island.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Hydraulic Conductivity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFSS</td>
<td>$5.71 \times 10^{-8}$</td>
</tr>
<tr>
<td>IBMS-SS</td>
<td>$1.09 \times 10^{-7}$</td>
</tr>
<tr>
<td>FZ</td>
<td>$9.48 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

5. CLIMATE AND RECHARGE MODELLING

5.1 Climate

The climate of Gulf Islands region is characterized by cool, dry summers and humid, mild winters. Mean monthly temperature on the islands generally ranges between 3.66°C to 4.23°C in the winter season (November to January), increasing to a range of 16.98°C to 18.39°C during the summer months (June to August). January is the coldest month on the islands, with a mean minimum temperature of 3.66°C, whereas the warmest month is August, with a maximum mean temperature of 18.39°C. Mean annual precipitation on the islands ranges from 658mm to 983mm, with the lowest annual precipitation recorded at Saturna Island and the highest on Saltspring Island. On average, the lowest monthly precipitation occurs in July (~23mm), and the maximum in November (~143mm). Approximately 80% of the mean annual precipitation falls between October to April, and less than 10% of the mean annual precipitation falls during the summer period. The reduced precipitation in the summer season is partly attributed to the rain-shadow effect created by the Olympic Peninsula of the USA to the south and the mountains of Vancouver Island to the west.
5.2 Recharge

Foweraker (1974) reported that all recharge to the groundwater system in the Gulf Islands comes from precipitation that falls during the late fall and winter months. He proposed that the rate at which precipitation recharges the aquifer depends on the nature and thickness of surficial deposits, vegetation cover, and the presence of preferential flow paths. He also suggested that the thickness and nature of surficial materials tend to be the major controlling factor on precipitation infiltrating and percolating into the subsurface, because the bedrock in formation in the area is mainly fractured. The current study demonstrates that the bedrock is variably fractured, and the IBMS-SS and FZ units have higher permeability than the LFSS domain. These results also suggest that zones of high fracture intensity with sub-vertical joints and fault zones are likely to be primary sites for recharge. Thus, in order to model recharge, the spatial variation in aquifer permeability, as well as the spatial variation in soil permeability and water table depth must be taken into account.

5.3 Recharge Modelling

The recharge model used for the study is the US Environmental Protection Agency’s Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al. 1994). Spatially-distributed recharge was mapped in ArcGIS 9.0, a GIS, by classifying the Gulf Islands region into recharge zones based on the distribution of hydrostructural domains (representing the aquifer media), the distribution of soils and slope, and the depth to the water table. The method employed here is the similar to that used in modeling recharge to the Grand Forks aquifer by Allen et al. (2004).

The HELP recharge modeling procedure involves first creating vertical percolation columns representative of the different recharge zones. A total of 48 vertical percolation columns were created for the study area, based on a combination of 1) three aquifer media classes (LFSS, IBMS-SS, and FZ) with Ksat values defined based on the values in Table 1, 2) four different soil classes (clay, topsoil (loamy sand overburden), glacial till, and gravelly sand) (Table 2), and 3) four depth to water table classes defined on the basis of the mid-point for each class (1.52m, 4.04m, 7.24m, 24.40m). Thus, there were 3 \times 4 \times 4 = 48 combinations. Each sediment column consisted of two layers, with the soil layer overlying the aquifer media. The water table formed the base of the column.

Prior to running the HELP model, a sensitivity analysis was performed. Each of the parameters - Leaf Area Index (LAI), Evaporative Zone Depth (EZD), Drainage Slope (S), Slope Length (SL), HELP Column Area (A) and Runoff Curve Number (CN) - were varied, and the mean annual water balances at the end of the recharge simulations compared. The analysis was performed with the same climate data on a 4 m thick vertical column profile with less fractured sandstone aquifer media, and a combination of all the different soil types.

The results of the sensitivity analysis suggest that EZD had a significant influence on recharge, LAI and CN had a moderate influence, S had a low influence, while SL and A had no influence on the recharge. Hence, appropriate values of the sensitive parameters were used for the recharge modeling. The estimated S and CN values were obtained from a Gulf Islands digital elevation model and U.S. L-THIA (2005), respectively. The vegetation cover on the islands is typically treed. A LAI of 100 cm was used to represent a typical root depth, and 100% runoff was assumed from surfaces where runoff was possible.

A 30-year weather series was generated using the LARS-WG stochastic weather generator using downscaled CGCM1 daily data as the input. HELP was then run for each percolation column to compute daily, monthly and annual recharge. Initial water content for all the layers was determined by simulating one year of hydrology, and then using the moisture storage obtained as initial values. The recharge results were then exported to MS Excel for analysis and then to ArcGIS 9.0 for mapping.

6. RECHARGE DISTRIBUTION

The spatially distributed mean annual recharge to the Gulf Islands aquifers ranges between 184 to 578 mm/yr, representing between 20% to 60% of the mean annual precipitation (Figure 3). Mean annual recharge for all recharge zones combined is approximately 45% of mean annual precipitation (Table 3).

Mean monthly recharge to the aquifer system varies between 14 to 41 mm/month (i.e., the average of value for the monthly means). Lower recharge (i.e., below the monthly mean) occurs between July and October, with the latter receiving the lowest recharge. Higher recharge occurs in December to March, while November, April and May receive moderate recharge. The monthly recharge pattern is a reflection of the temporal distribution of precipitation, which is the only source of recharge to aquifer.

### Table 2: Soil properties used in HELP modeling

<table>
<thead>
<tr>
<th>Soil Class</th>
<th>Thickness (m)</th>
<th>Ksat (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Soil</td>
<td>1.43</td>
<td>1.00x10^{-4}</td>
</tr>
<tr>
<td>Clay</td>
<td>3.96</td>
<td>2.00x10^{-7}</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>3.03</td>
<td>1.00x10^{-4}</td>
</tr>
<tr>
<td>Gravelly Sand</td>
<td>0.73</td>
<td>1.00x10^{-2}</td>
</tr>
</tbody>
</table>

### Table 2: cont’d

<table>
<thead>
<tr>
<th>Soil Class</th>
<th>Porosity</th>
<th>Field Capacity</th>
<th>Wilting Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Soil</td>
<td>0.45</td>
<td>0.130</td>
<td>0.058</td>
</tr>
<tr>
<td>Clay</td>
<td>0.47</td>
<td>0.284</td>
<td>0.135</td>
</tr>
<tr>
<td>Glacial Till</td>
<td>0.35</td>
<td>0.105</td>
<td>0.047</td>
</tr>
<tr>
<td>Gravelly Sand</td>
<td>0.42</td>
<td>0.045</td>
<td>0.018</td>
</tr>
</tbody>
</table>
Table 4: Mean annual water balance from HELP simulations for the different time periods. (Note: % Ppt = precipitation).

<table>
<thead>
<tr>
<th>Parameters (mm)</th>
<th>Current</th>
<th>% Ppt</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRECIPITATION</td>
<td>880.48</td>
<td></td>
</tr>
<tr>
<td>RUNOFF</td>
<td>47.38</td>
<td>5.38</td>
</tr>
<tr>
<td>EVAPOTRANSPIRATION</td>
<td>435.24</td>
<td>49.43</td>
</tr>
<tr>
<td>RECHARGE</td>
<td>394.81</td>
<td>44.84</td>
</tr>
<tr>
<td>STORAGE</td>
<td>3.05</td>
<td>0.35</td>
</tr>
</tbody>
</table>

December to June contributes to recharge, while less than 40% of precipitation from July to November is received as recharge. Highest recharge on the islands is in December, whereas the lowest rates occur between July and October.

The upper range of the recharge estimates is higher than estimates based on well hydrograph analysis. Typically well hydrograph analyses yield less than 200 mm/year of recharge for the Gulf Islands. Thus, there remains some uncertainty in the absolute values of present day recharge on the Gulf Islands.

8. ACKNOWLEDGEMENTS

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References


