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09-04

ENGLISHMAN RIVER WATERSHED

GROUNDWATER FLOW THROUGH BEDROCK CONTRIBUTING TO THE ENGLISHMAN RIVER

For:

MVIHES
MID VANCOUVER ISLAND HABITAT ENHANCEMENT SOCIETY

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1. Introduction

This report describes a community-based program that was implemented in order to begin characterizing and understanding the interactions between the bedrock aquifers and surface water in the Englishman River (ER) Watershed.

Background

Since 2009, the Mid Vancouver Island Habitat Enhancement Society (MVIHES) has initiated a number of programs that have investigated the interactions between surface water and groundwater in the Englishman River (ER) Watershed. The initial program provided a desktop review of the groundwater/surface water monitoring in the ER Watershed titled *Englishman River Watershed (Background information).* This set the stage to design and implement the MVIHES Groundwater study Phase 1, a community based, groundwater watershed monitoring program. The objectives of the Phase 1 study were to update the knowledge about the aquifers in the surficial sediment deposits (sand and gravel – overburden) along the ER, and to characterize the dynamic flux of groundwater between the aquifers and the river. This program concentrated on the lower portion of watershed (below 16.5Km – measured from the estuary) in order to study the sand and gravel aquifers. By studying the overburden aquifers it was observed that the bedrock aquifers also played a potentially significant role in groundwater/surface water interactions; and as such one of the recommendations was to characterize the groundwater flow in the bedrock aquifers. For more details on Phase 1 and the ER watershed see the reports *Lower Englishman River Watershed Groundwater and Surface Water Interactions (2012),* and *Englishman River Watershed (Background information) (2009)* which can be found at the following link

http://gwsolutions.ca/wp-content/uploads/2013/11/ER-Watershed-GWS.pdf.

Based on the results from the Phase 1 study and the recommendation of monitoring a network of wells installed in the bedrock aquifer, the MVIHES initiated the Groundwater study Phase 2 with the goal of qualifying and quantifying the role of bedrock in the groundwater dynamics of the ER Watershed. An approach similar to the one utilized in the Phase 1 study was applied, based on community involvement and aquifer monitoring.

Objectives

The groundwater contribution to the ER is thought to be significant, especially during the summer months during low flow conditions. Overburden aquifers are present in the lower part of the ER watershed (below 16.5 Km). However, bedrock is present across the whole watershed, and at or close to surface above the ER waterfalls (the 16.5 Km mark). Thus the importance of better defining the groundwater flows through bedrock.

The main objectives of this study were to select an applicable methodology that would characterize the groundwater regime through bedrock, and to apply this methodology to quantify the role-played by bedrock, assuming a water budget for the watershed.

This study examines the entire watershed with a focus on the bedrock groundwater movement that occurs above the 16.5 Km mark (ER waterfall) and is south of the yellow line in Figure 1. However, bedrock flow does occur below the overburden aquifers (below 16.5 Km) and it is in this area where additional information is available from drinking water wells, regional studies etc.

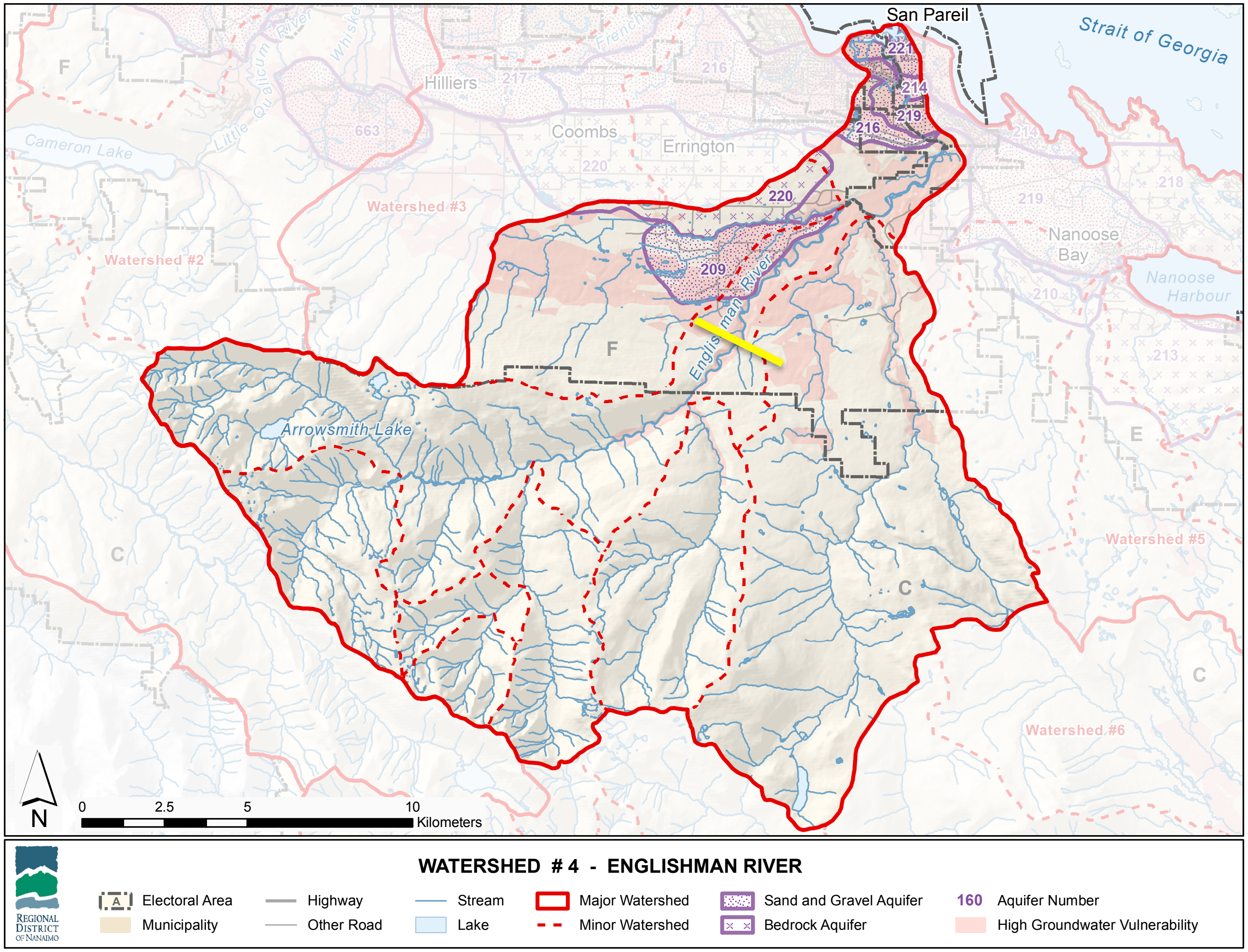

Figure 1: Englishman River Watershed (source RDN)

2. Bedrock Flow and Mountain Block Recharge

Understanding the movement of groundwater through fractured bedrock is very complex because fractured bedrock is not a homogenous porous medium. There, groundwater flows through multitude fractures, big and small, open or partly sealed, short and long, connected or disconnected, etc. Due to these unique patterns, estimating hydraulic characteristics (permeability, porosity, transmissivity etc.) is difficult and can vary in orders of magnitude across short distances.

Groundwater flow through fractured bedrock that contributes to aquifers in the lower reaches of watersheds is referred to as "mountain block recharge (MBR)" in technical terms. Figure 2 shows this movement, emphasizing the deep regional flow patterns that can be associated with MBR.

Although this concept is well established within the scientific community it is still a relatively new field of research with a lot of "work in progress". Due to the complexity of groundwater movement through bedrock it is not possible to directly measure the flow, therefore, a variety of different methods have been developed in attempts to quantify MBR. Subsequently, quantifying techniques typically use the measurement of surrogate parameters to estimate the MBR.

Furthermore, when assessing bedrock flows another level of complexity is added when examining major faults zones. Faults can act as either conduits (increase flow), barriers (hinder flow), or as conduit-barriers to the flow of water. In terms of the ER watershed these faults can additionally be either a source (discharge into the river) or drain of water (discharge from the river) to the ER. Assessing flow through faults is a difficult task and is typically accomplished through conceptual or computer modelling. Depending on the scale of analysis the hydraulic properties can again vary in orders of magnitude increasing the level of uncertainty.

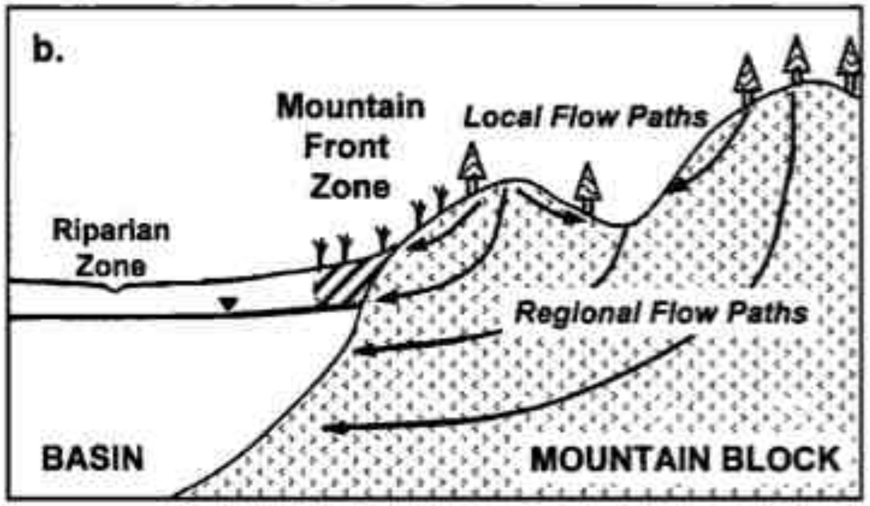

Figure 2: Mountain block recharge depicting water originating in upper mountains flowing into lower basin.

3. Completed work

The work accomplished was a continuation of the approach developed in Phase 1. The design was to collect information on the behaviour of bedrock aquifers in the ER watershed, to assess the elevation of the water table in the fractured bedrock, to estimate the groundwater regime (groundwater flow path), identify bedrock topography and major fault zones in the ER watershed, and to describe the interconnections between the bedrock aquifers and the ER and overburden aquifers through an estimation of the groundwater flux of MBR and major faults discharging to the ER and overburden aquifers.

Well Monitoring

A desk review of the BC well database was completed and all bedrock wells within the ER watershed and the immediately surrounding area were identified. The remainder of the completed work has been community-based; well owners were invited to offer their wells for monitoring of the fluctuation of the water table. The following was completed:

- A total of 11 drilled wells were identified and monitored; 9 electronic data loggers were re-positioned from wells in the Phase 1 study, 3 remained in their current wells as they were identified to be in bedrock. The data started being collected on August 18, 2009 and is on-going;

The locations of all monitored locations are shown below in Figure 3.

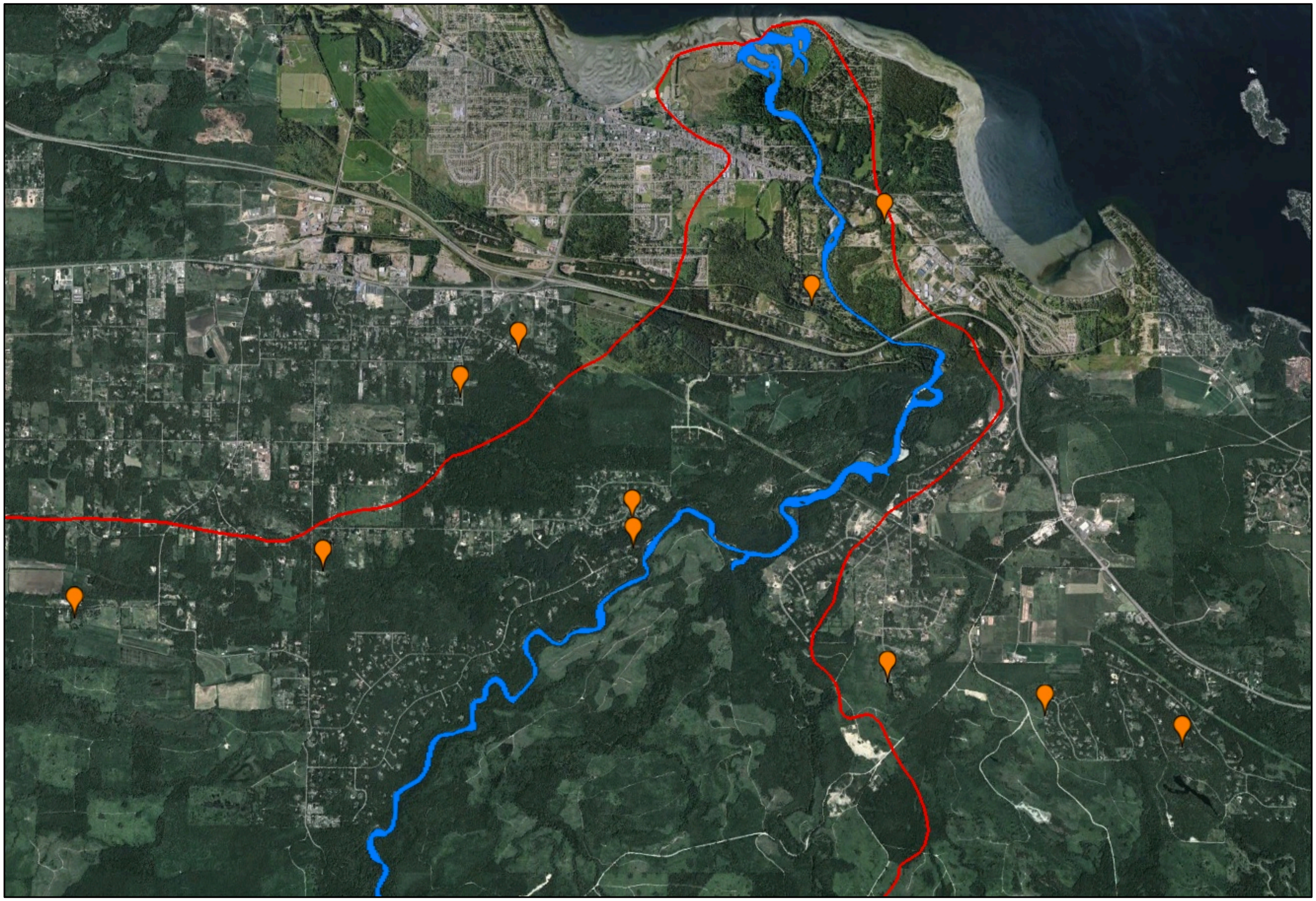

Figure 3: Location of 11 bedrock monitoring wells

Geologic and Hydrogeologic Setting

The bedrock geology and the major fault zones were mapped (Figure. 4 & 5) and the bedrock topography in the lower 16Km of the ER watershed assessed (Figure 6). There are four major rock types in the ER watershed with unique hydrologic properties that is taken into consideration throughout the analysis. Eight major fault zones occur within the ER watershed, which are exhibited as purple lines in Figure 5. Based on the location of major fault zones and elevation flow directions were estimated for the three major faults present within the upper watershed (yellow arrows).

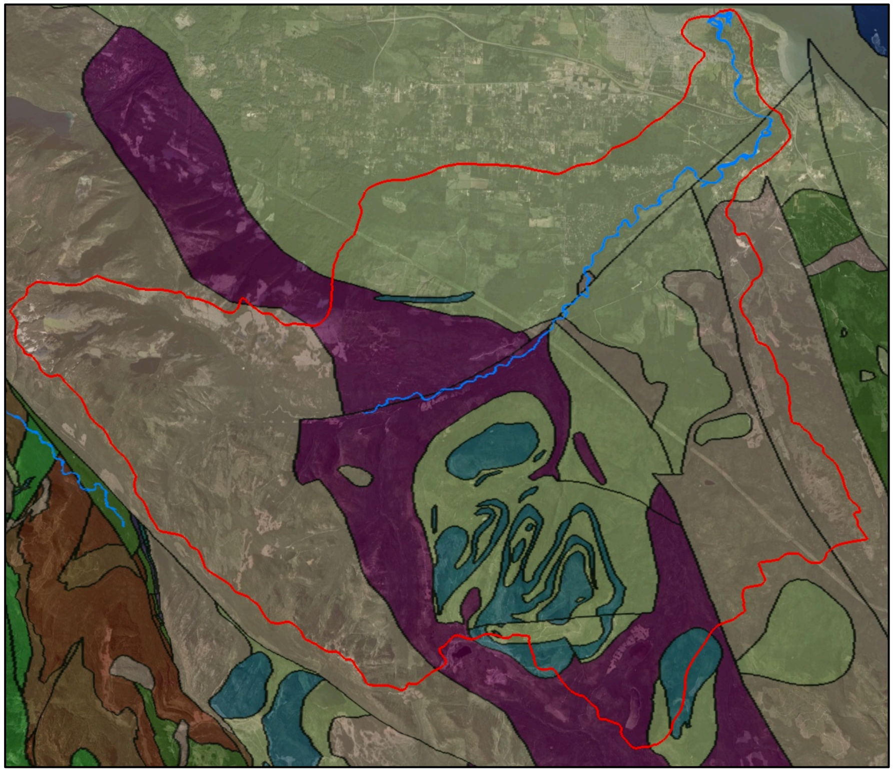

Figure 4: Geology of Englishman River watershed

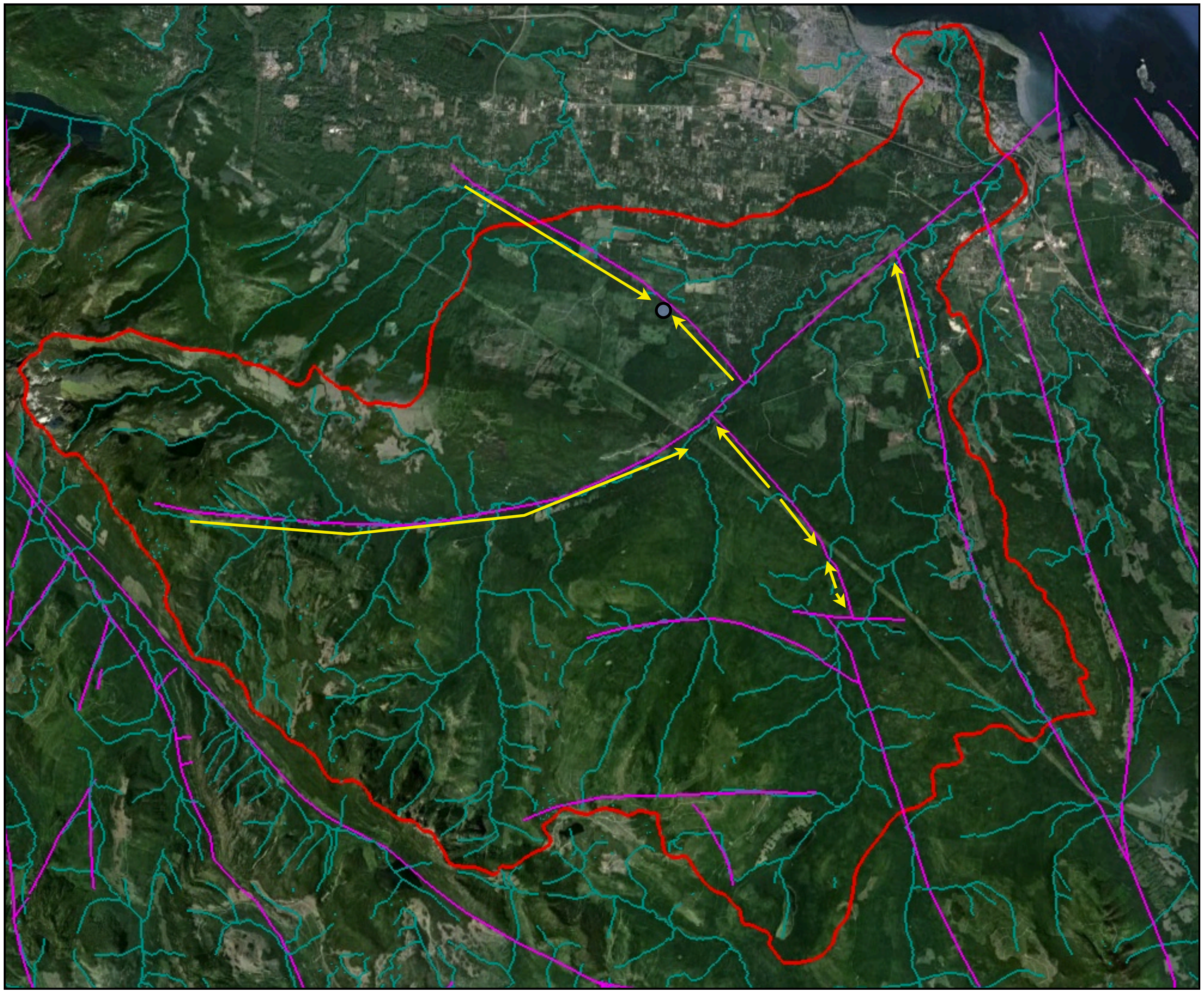

Figure 5: Major faults (purple lines) and potential flow direction (yellow arrows) in the Englishman River watershed

The bedrock topography of the lower 16 Km was assessed through GIS mapping which produced a map of depth to bedrock from surface.

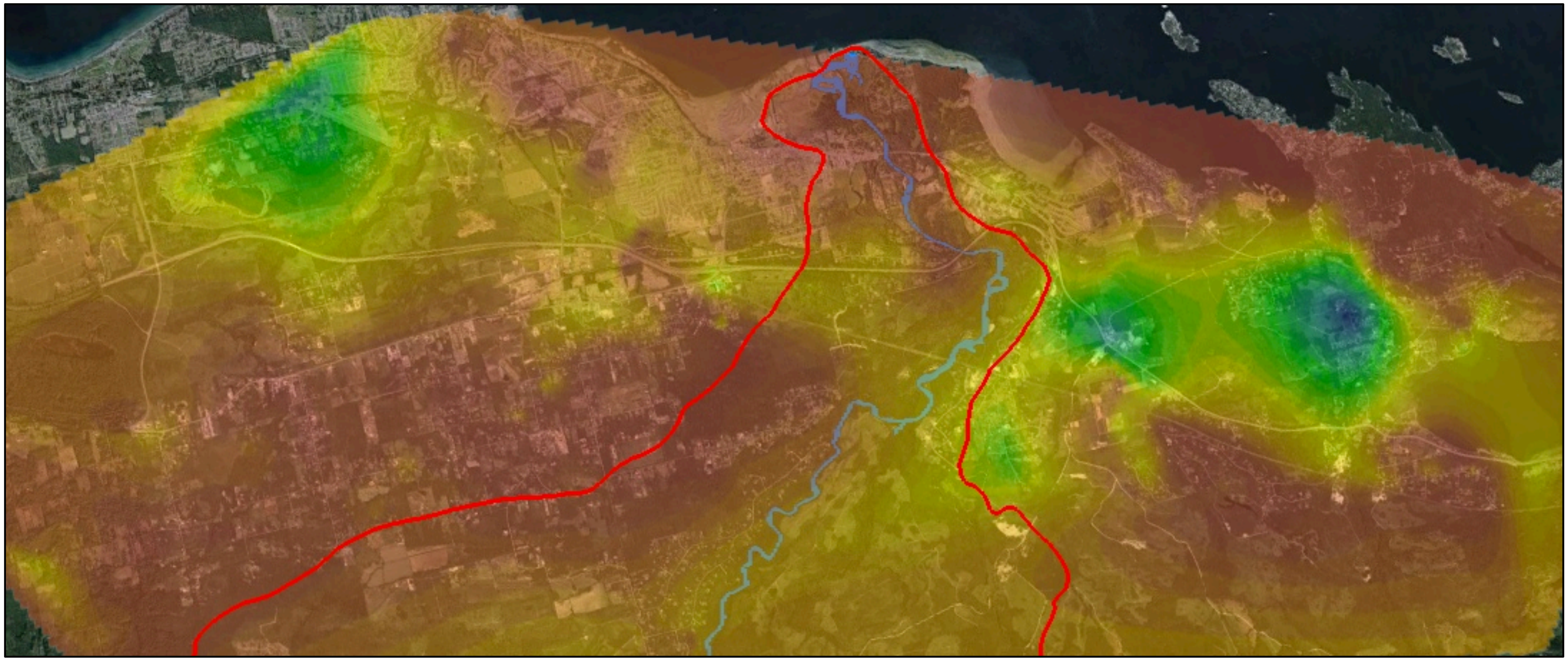

Figure 6: Map of depth to bedrock with blue/green shading being deep points and yellow/reds shallower

A literature review was completed on fault zones hydrology to have a better understanding of the hydraulic mechanisms present in the ER watershed. Simple 3D models were produced of the lower watershed to illustrate potential groundwater regimes in fractured bedrock. Figure 7 below shows one such 3D model that represents the western portions of the ER watershed capturing two bedrock wells in the monitoring network.

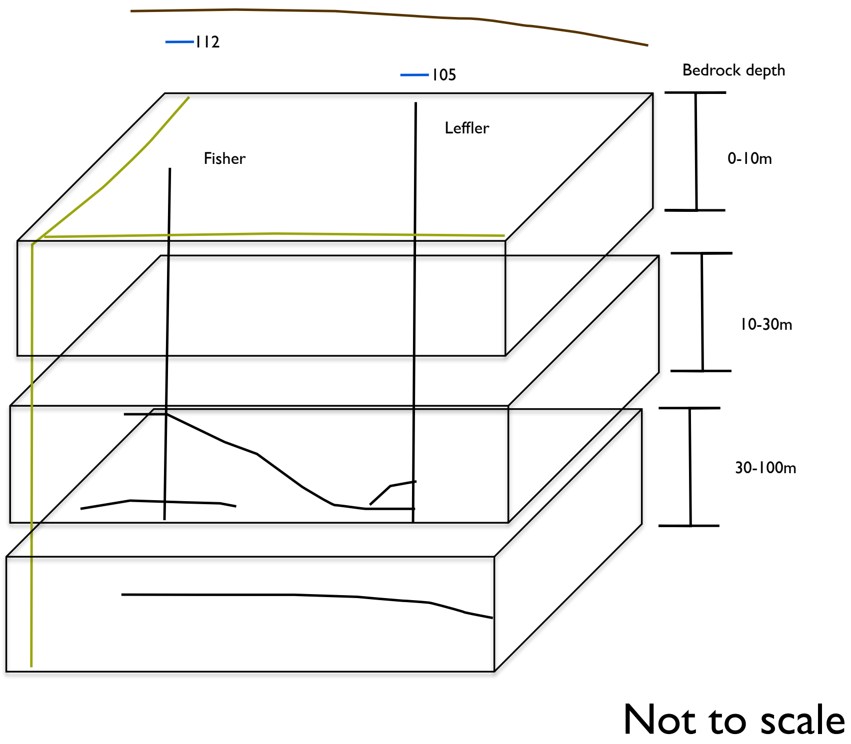

Figure 7: Simple 3D model highlighting potential fracture regimes

Many assumptions had to be made, therefore an important section of this report is the recommendations we make to confirm or refute these assumptions to refine our understanding of the groundwater flow through the fractured bedrock.

Calculation of mountain block recharge and groundwater flux

A literature review was completed on mountain block recharge to evaluate current methods that have been applied to quantify MBR and to assess what could be applied in the ER watershed. Through this research it was determined that the best approach would be through a simple watershed budget as shown below in Equation 1, combined with a base flow analysis on the ER.

$$P = I + RO + ET \quad \text{(Eq.1)}$$

P, is the average precipitation in the watershed; I, is the infiltration into the bedrock; RO, is the surface runoff; and ET, is evapotranspiration. Applying this method to the partitioning on MBR was also accomplished through a basic watershed budget.

$$MBR = DF + FF + FT \quad \text{(Eq. 2)}$$

Where MBR is mountain block recharge; DF is the diffuse flow; FF is the fault flow; and FT is the flow through (or water that continues to overburden aquifers and the ocean).

In 2013 the RDN released a report titled *Water Budget Project: RDN Phase One (Vancouver Island)*; section 3 of this report presents a water budget for the ER watershed. In the RDN report an estimation of the annual precipitation and evapotranspiration was generated through extrapolation in GIS; these values were used in our analysis. However, the evapotranspiration appeared underestimated, so in our calculations it was increased based on a similar watershed on Vancouver Island.

The base flow contribution (the flow level from groundwater) was estimated using WHAT: Web-based Hydrograph Analysis Tool[1] with data from the Water Survey of Canada (WSC) station located just above the estuary (08HB002). This tool is quick and easy to use requiring only average stream flow data, however, in order to keep the calculation simple there are only three options that can define the aquifer conditions and only one can be selected for the analysis. This means that the base flow is a rough estimate and an analysis tailored for the ER would produce more accurate data. Currently, a model is being produced by Natural Resource Canada (NRCan) of the ER watershed that will generate a specific base flow analysis. Once this data is published this will be an excellent source of information to enhance the model. The graph below (Figure. 8) illustrates the base flow (from both fractured bedrock and overburden aquifers) compared to the average stream flow based on the 41 years of stream flow data between 1913-2012 (including the contribution from the Arrowsmith dam).

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[1] https://engineering.purdue.edu/~what/

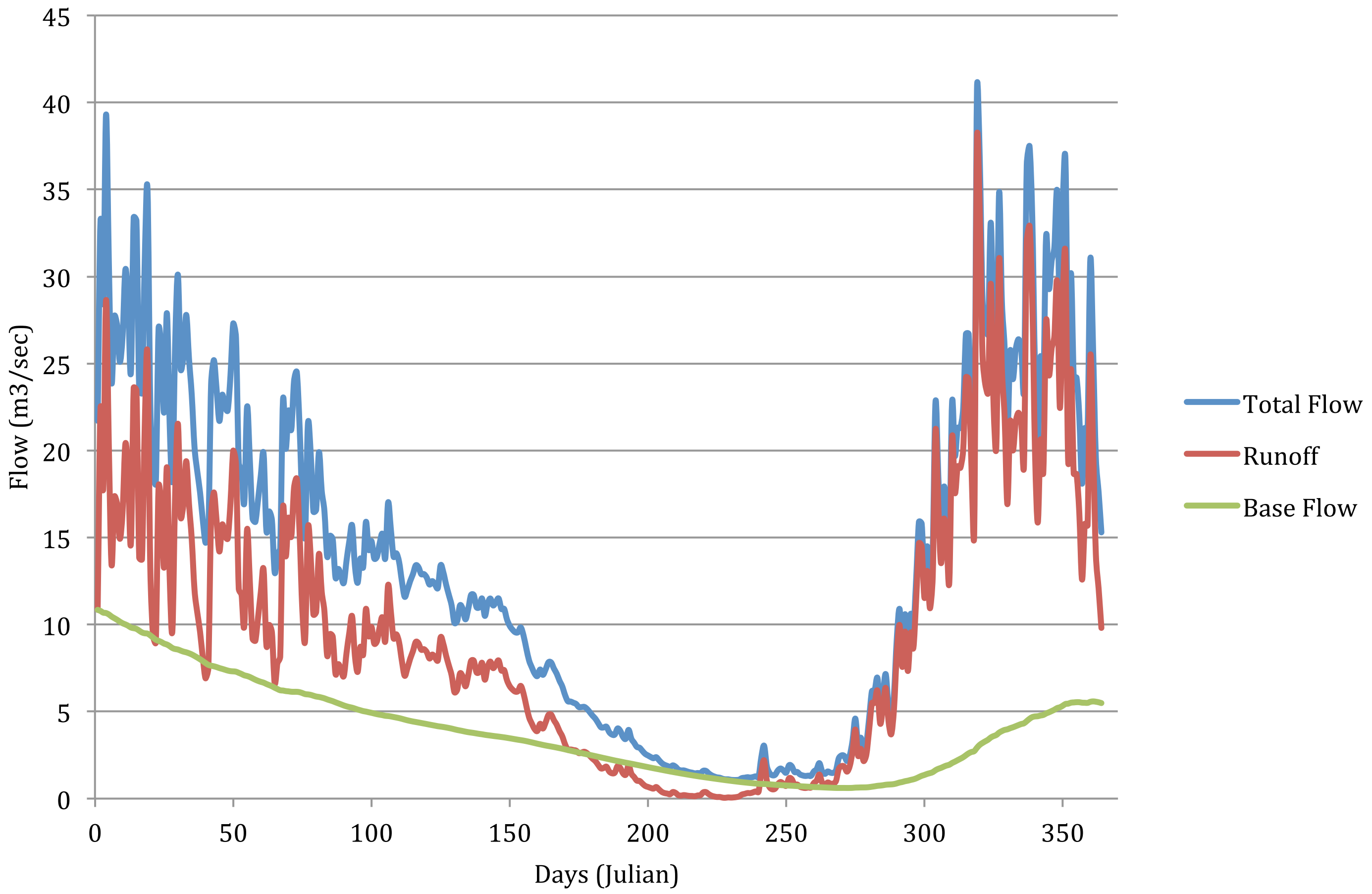

Figure 8: Average stream flow breakdown to runoff and base flow

We have completed a first estimate of the MBR using a conceptual model and spreadsheet calculations.

Conceptual Model

The conceptual model considers the following:

- Infiltration will get directly into bedrock above 16.5 Km (corresponding to an approximate elevation of 100m) because bedrock is either outcropping or covered by a thing veneer of soil.
- Infiltration is equal to mountain block recharge and has four potential discharge points (through faults, directly into river, overburden aquifer, and ocean).
- The faults play an important role in controlling the flow and define the boundaries of "fractured bedrock sub-watersheds" (Figure 9).

Spreadsheet calculation

Through the spreadsheet calculations the following values were estimated:

- Using the contribution of overburden aquifers calculated in Phase 1 the base flow was separated into bedrock and overburden portions.
- Separating the flow between diffuse flow and fault flow was accomplished through Darcy's law calculations utilizing hydraulic characteristics from literature.
- Based on Equation 2, the watershed budget was used to balance the flow and determine the MBR that is discharged to sources other than the river.

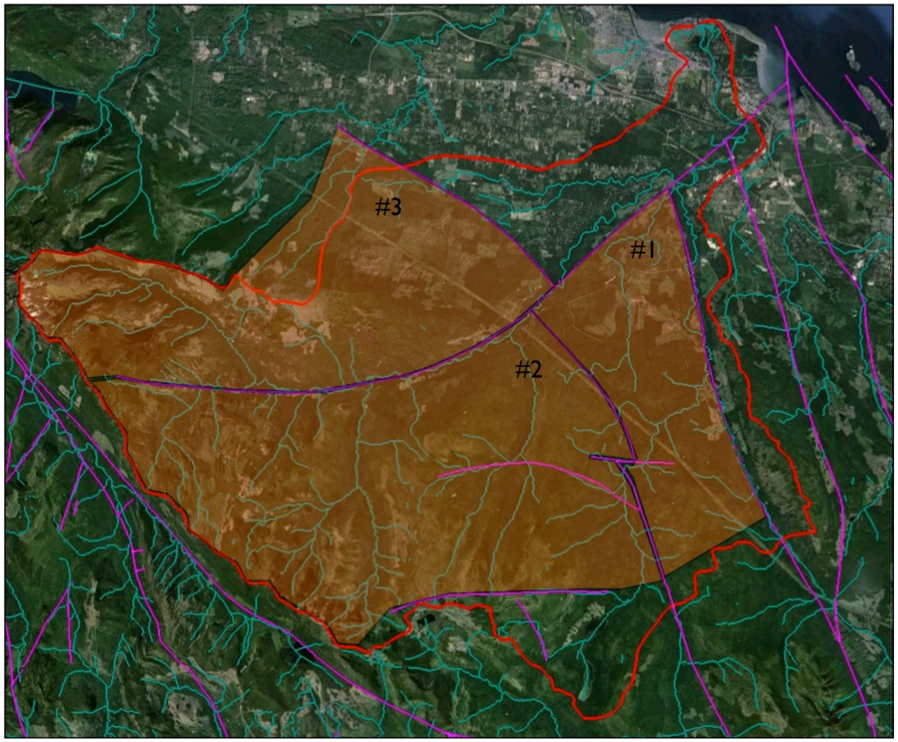

Figure 9: Identification of the three major fractured bedrock sub-watersheds

4. Results

Piezometric (Water Table) Levels

Piezometric levels were monitored in 11 drilled wells using data loggers and manual measurements. Figure 10 & 11 illustrate the fluctuating water levels recorded with the data loggers. These graphs are separated based on elevation in order to easily identify patterns. In order to present the most accurate aquifer conditions the graphs were constructed using water level measured at 4:00 am. At this time it is assumed that the wells have fully recovered from pumping and the aquifer is considered at rest. Precipitation is included on the graphed in order to correlate the observed water table fluctuations with potential recharge due to precipitation.

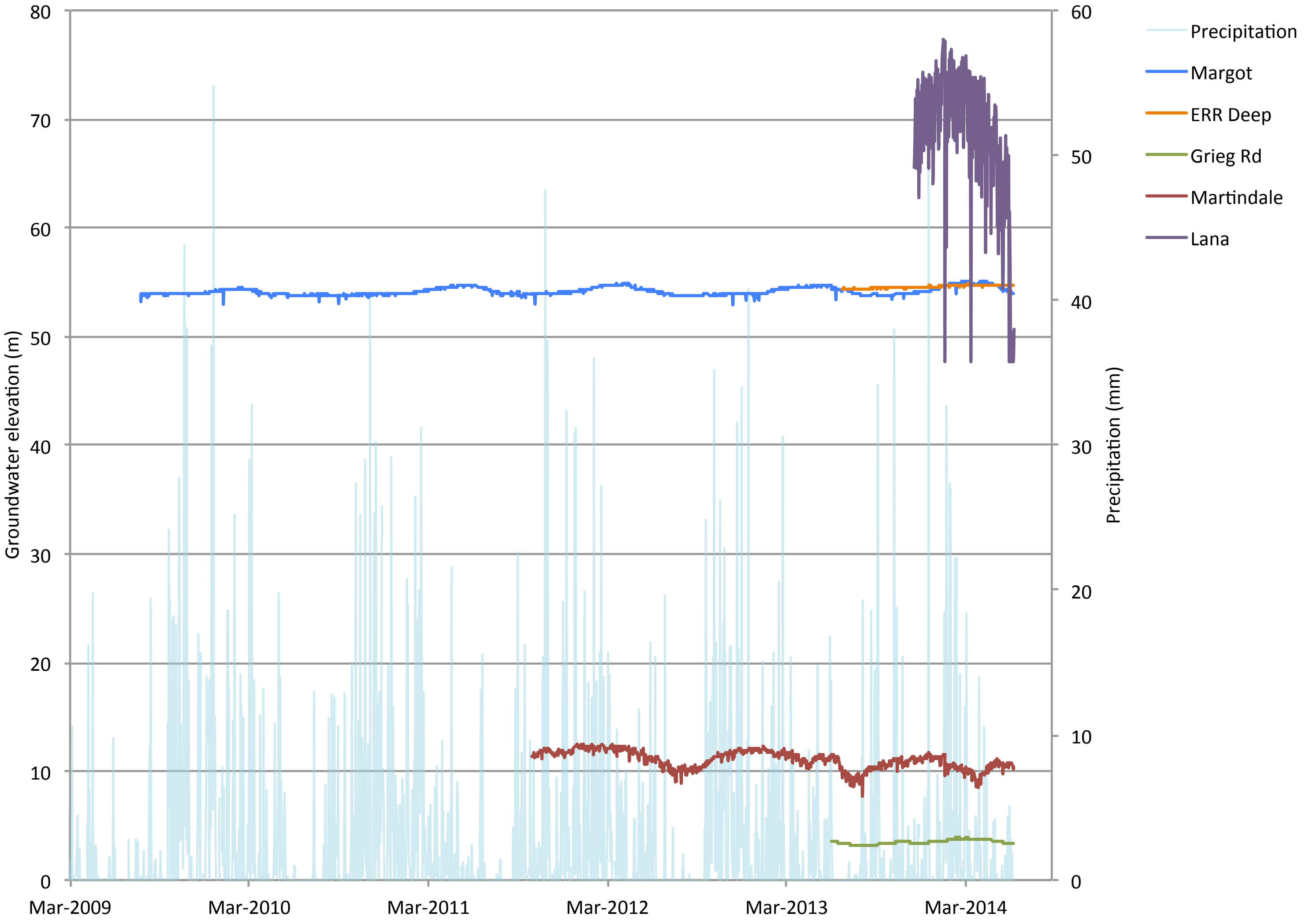

Figure 10: Piezometric levels (lower then 80m) recorded by data loggers and precipitation

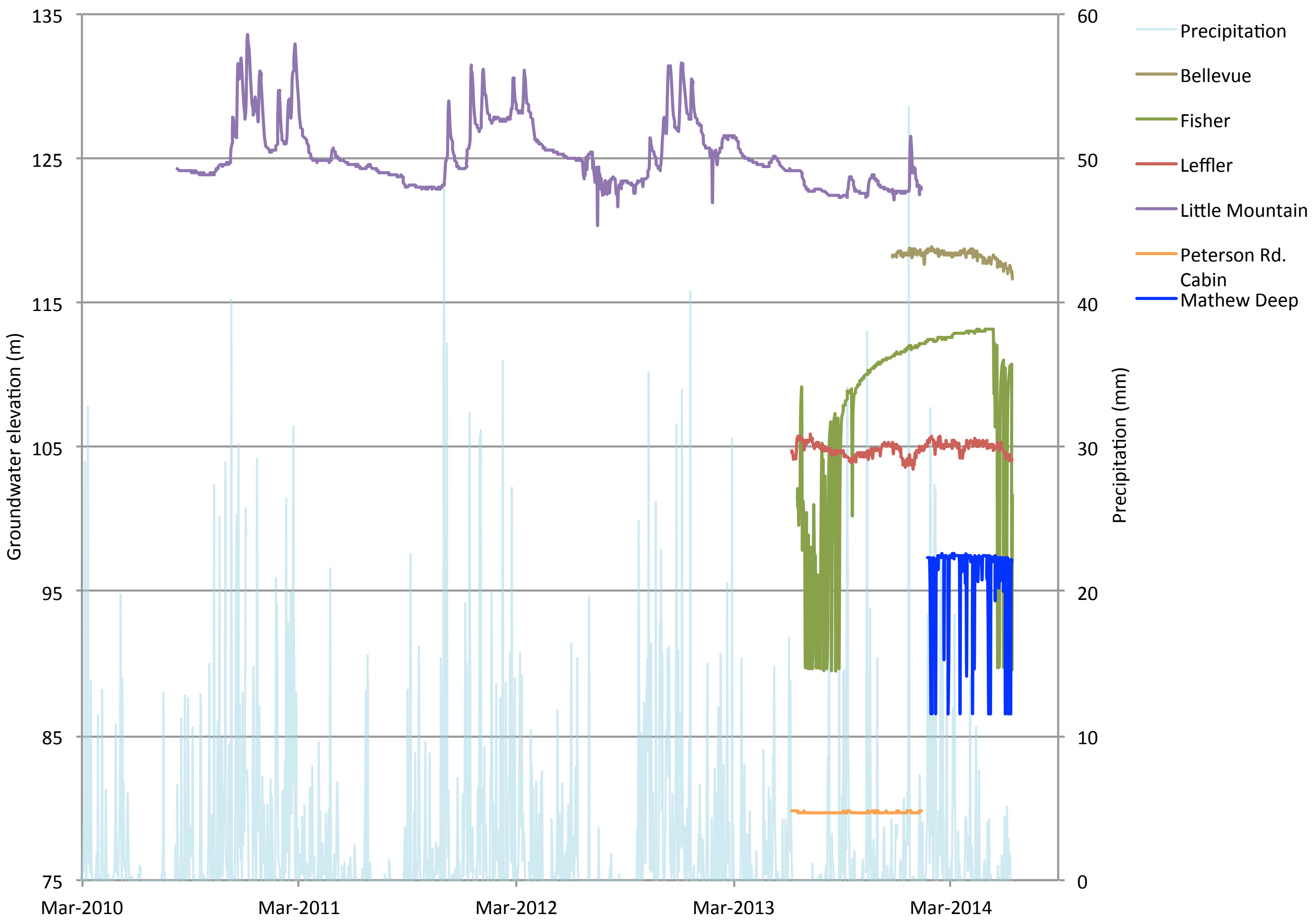

Figure 11: Piezometric levels (above 80m) recorded by data loggers and precipitation

Four wells (Little Mountain, Martindale, Margot, and Lana) have distinct trends that correlate with precipitation, suggesting that there is a connection between the surface and the bedrock fractures.

The seasonal fluctuation of the water level is presented below in Figure 12 and range between 0.2 m. and 13 m. A small fluctuation can indicate that the monitoring well is not strongly connected to the surface and is therefore not influenced by changes in precipitation compared to wells that experiences large fluctuations could be strongly connected to changes in precipitation.

Figure 12: High and low water levels recorded in 2013-2014 and direction of vertical groundwater movement in purple arrows

Groundwater Flow and Hydraulic Gradient

Hydraulic gradient dictates the direction of groundwater flow both horizontally and vertically. It is calculated by the difference between two hydraulic heads (water levels) over distance. Horizontally, it is represented by the slope of the water table and vertically, it provides information whether groundwater is moving upward or downward in the studied aquifers. Based on the minimum water levels recorded by the data loggers and other known water levels in overburden aquifers or surface water bodies that were near the wells completed in bedrock, the vertical movement of water was estimated. The purple arrows (Figure 12) indicate a majority of locations where the direction of the vertical movement of groundwater in the fractured bedrock is upward.

Horizontally, the general direction of the groundwater flow through the bedrock trends towards the ocean. In addition, the shape of the piezometric contours indicates that the ER acts as a drain, collecting groundwater flowing in the bedrock. Figure 13 provides potential piezometric contours and direction of water flow in blue arrows across the ER watershed. Based on the simple 3D models generated the depth at which consistent water production occurred (based on the reports from drillers of water bearing fractured zones) was typically between 10 m - 30 m into bedrock, which is generally below the weathered and assumed more transmissive zone.

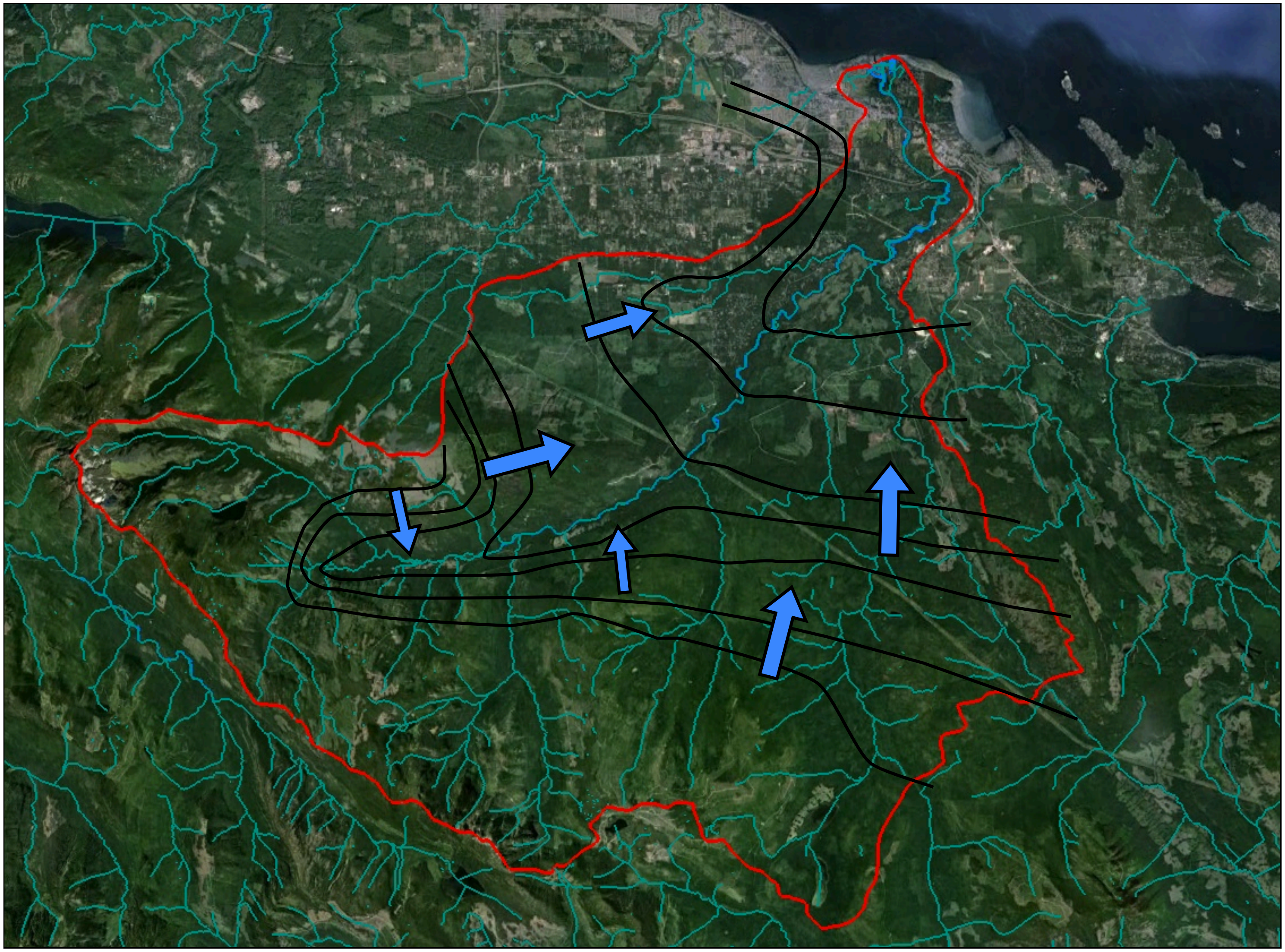

Figure 13: Estimated bedrock flow paths across the ER watershed

From the base flow analysis approximately 80% of the summer low flows originates from groundwater sources. Using the fluxes determined in the Phase 1 study we were able to separate the overburden and bedrock aquifer contributions and an estimated 50% of base flow in summer months comes from bedrock sources.

Groundwater Flux

Similarly to the Phase 1 report once the direction of flow is determined the next step is to estimate the flux of groundwater towards the ER. For a detailed explanation of groundwater flux see the report: *Lower Englishman River Watershed Groundwater and Surface Water Interaction* (GW Solutions, 2012).

As this study focused on bedrock and faults a few differences were noted from the Phase 1, which are as follows:

- Values of hydraulic conductivity were estimated from literature based on rock type.
- Diffuse flow was separated from fault flow by first estimating the flow through the bedrock and then the remaining value for infiltration was multiplied by the percentage the fault catchment is of the ER watershed.
- Using Equation 2 the flow through values were calculated.

Through the spreadsheet calculations the diffuse and fault flows were estimated for both summer (low flows) and mean annual conditions. It was found that annually the bedrock contributes approximately 27% of the flow, predominantly through the faults (25%); and in summer conditions it contributes 50% of the flow and 45% enters through the faults. Figure 14 was generated to visually represent the quantity of water flowing through the fault zones and entering the ER with the associated elevation. The three major faults intersect the river at 19.5 km, 17.5 km, and 9 km. The summer flux is shown in orange and the annual flux in green.

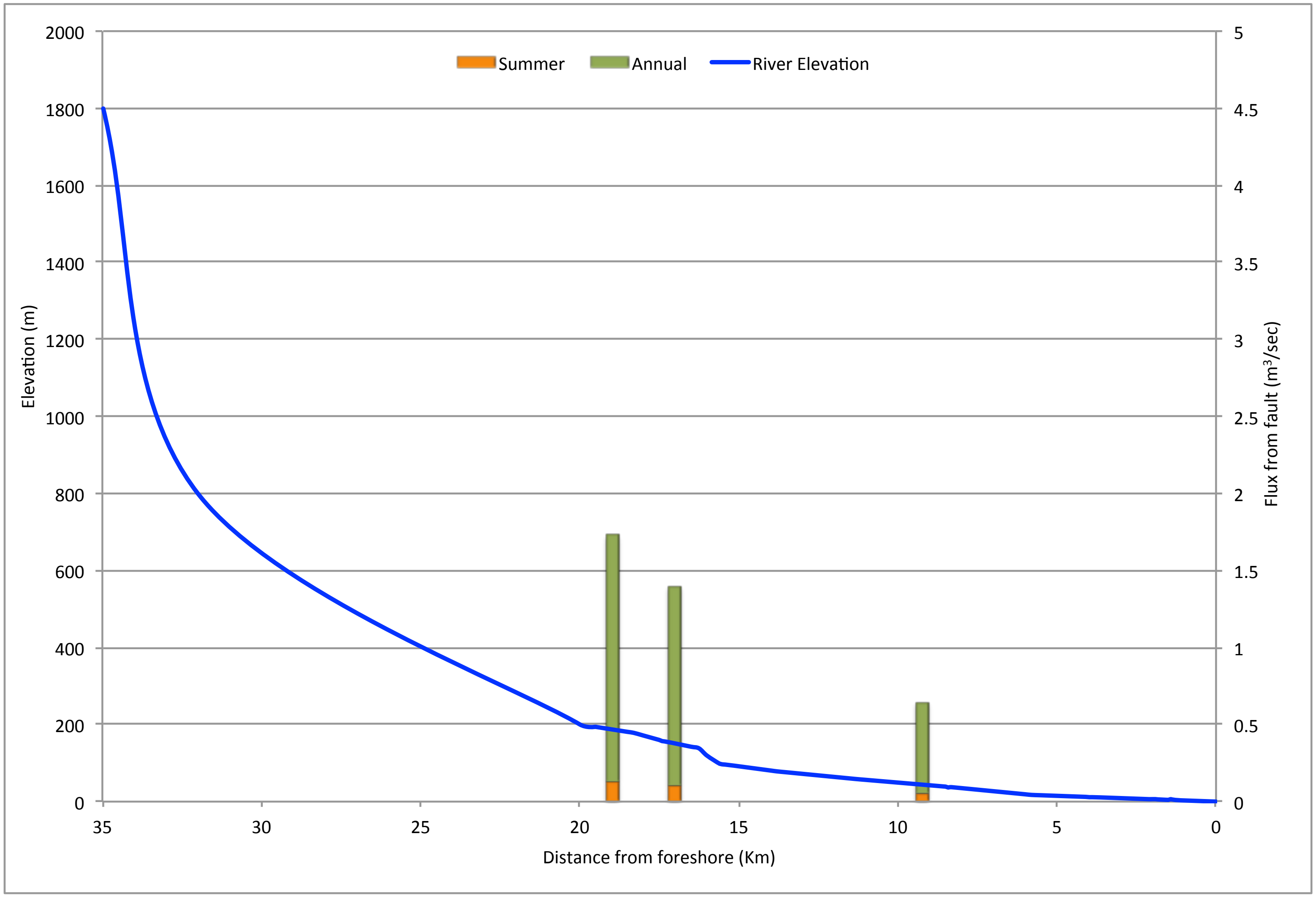

Figure 14: Englishman River elevation with flux of each fault

The estimated groundwater flux through the major mapped faults is further illustrated in Figure 15

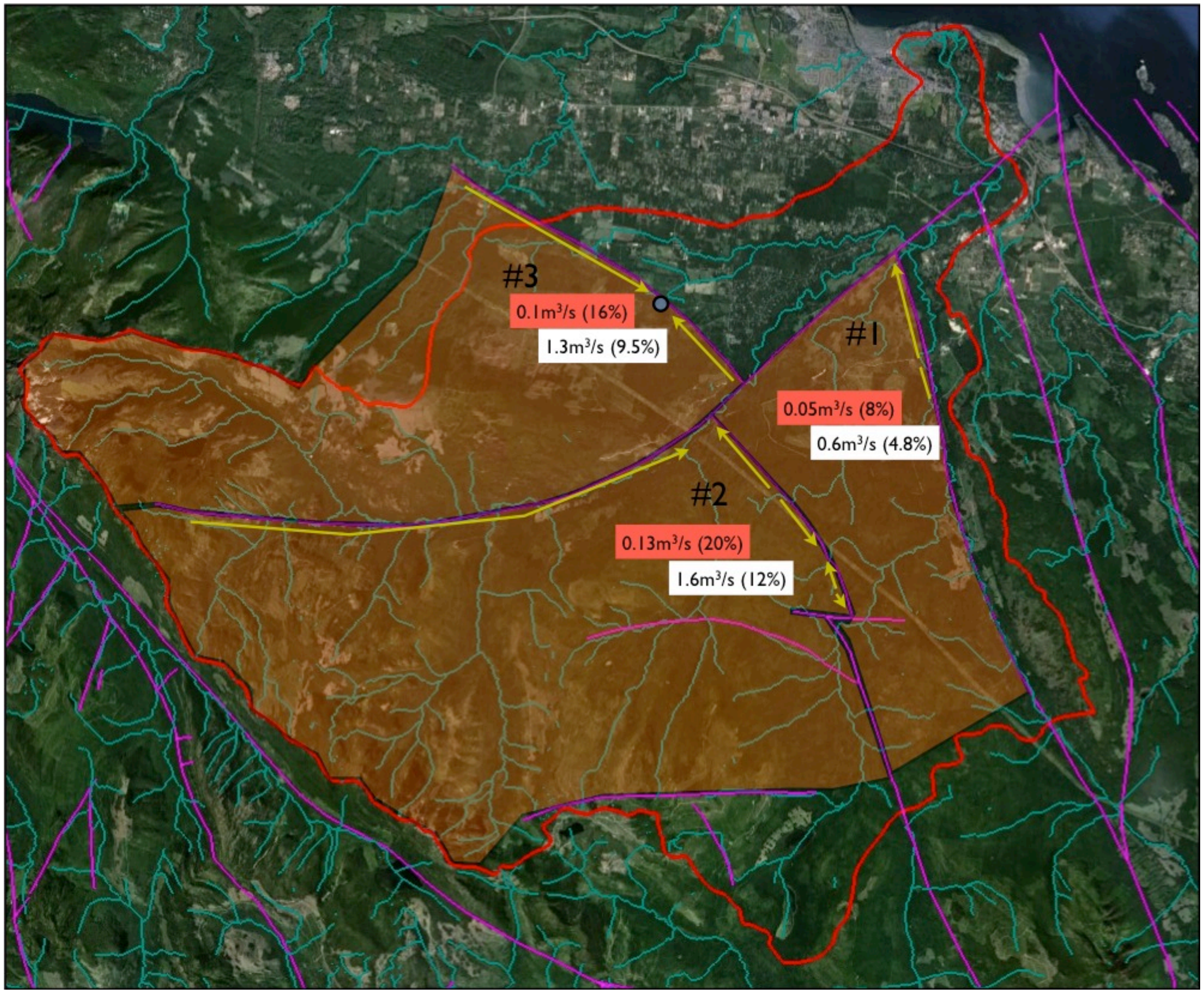

Figure 15: Englishman River watershed with fault catchment areas and fluxes

Not all groundwater flowing through the bedrock will end up discharging into the ER. Some will flow down to the lower portion of the watershed and will discharge to the overburden aquifers driven by an upward hydraulic gradient or to the ocean. We estimate that approximately 22% of the annual flow (or 9 x 10^7 m^3/yr) transiting through the bedrock feeds the overburden aquifers and discharges to the ocean.

5. Conclusions

Based on the completed study, GW Solutions draws the following conclusions:

- Local residents who provided access to and monitoring of their wells were key in the completion of this study.

- The lithology indicates that the majority of the watershed (area above 16.5 km) consists predominantly of bedrock either outcropping or only covered with a thin soil veneer. Therefore, the recharge originating in the upper watershed primarily occurs as mountain block recharge (MBR).

- The majority of the bedrock flow (below 16.5 km) appears to occur under the highly weathered bedrock, indicating that there are deeper regional flow paths occurring within the watershed, coinciding with the assumption that MBR plays a significant role in the watershed.

- The correlations between a rise in piezometric levels with precipitation in some monitored wells suggests that these wells are closely connected to recharge areas where precipitation is infiltrating into the bedrock.

- Approximately 80% of the summer low flow originates from groundwater sources, as estimated using the base flow separation method. This 80% consists of 30% from overburden aquifers contribution (Phase 1 study) and 50% from bedrock sources. These percentages may be slightly over estimated because they do not take into account the flow released by the Arrowsmith dam.

- The major faults within the ER watershed appear to play a role in the interaction between the bedrock aquifers and the river. During the summer months approximately 45% of the bedrock contribution is funnelled through these fault zones. However, these results are based on a number of assumptions, and are still conceptual. Field studies should be undertaken to confirm these assumptions.

- The general upward hydraulic gradient trend from the bedrock aquifers across the watershed supports the assumption that the bedrock aquifers are acting as a recharge to the ER and overburden aquifers.

6. Recommendations

In order to improve the knowledge and understanding of the complex bedrock flow within the ER watershed GW Solutions makes the following recommendations:

- The characteristics of the aquifers in the upper watershed need to be better defined in order to refine the estimation of groundwater fluxes and understand the influences of faults. Drilling and testing of monitoring wells would provide valuable information.
- An assessment of the ER temperature (spot measurements every 50 m) from 16.5 km to the source. This could identify points of groundwater seeps and help identify locations for the following recommendation.
- The installation of stream gauges at locations near known fault zones could provide information about the flow attributable to the fault. This information could help distinguishing if the faults are either a source or drain of water, and if there is a contribution, what the potential flux could be. Ideal locations would be up and downstream of known fault zones.

7. Acknowledgments

This work has been initiated by the Mid Vancouver Island Habitat Enhancement Society (MVIHES). This study was made possible by the grants or in-kind support provided by the Real Estate Foundation of BC, TimberWest, GW Solutions Inc, Living Rivers, the Regional District of Nanaimo, TD Friends of the Environment, and Pacific Salmon Foundation, and by the volunteers who participated in the project.

8. Closure

Conclusions and recommendations presented herein are based on available information at the time of the study. The work has been carried out in accordance with generally accepted engineering practice. No other warranty is made, either expressed or implied. Engineering judgement has been applied in producing this letter-report.

This letter report was prepared by personnel with professional experience in the fields covered. Reference should be made to the General Conditions and Limitations attached in Appendix 1.

GW Solutions was pleased to produce this document. If you have any questions, please contact me.

Yours truly,

PROFESSIONAL
PROVINCE OF
G. R. WENDLING
BRITISH COLUMBIA
ENGINEER

Gilles Wendling, Ph.D., P.Eng.
President
GW Solutions Inc.

Appendices

Appendix 1. GW Solutions Inc. General Conditions and Limitations

APPENDIX 1

GW SOLUTIONS INC. GENERAL CONDITIONS AND LIMITATIONS

This report incorporates and is subject to these “General Conditions and Limitations”.

1.0 USE OF REPORT

This report pertains to a specific area, a specific site, a specific development, and a specific scope of work. It is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site or proposed development would necessitate a supplementary investigation and assessment. This report and the assessments and recommendations contained in it are intended for the sole use of GW SOLUTIONS’s client. GW SOLUTIONS does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than GW SOLUTIONS’s client unless otherwise authorized in writing by GW SOLUTIONS. Any unauthorized use of the report is at the sole risk of the user. This report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of GW SOLUTIONS. Additional copies of the report, if required, may be obtained upon request.

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This report is based solely on the conditions which existed within the study area or on site at the time of GW SOLUTIONS’s investigation. The client, and any other parties using this report with the express written consent of the client and GW SOLUTIONS, acknowledge that conditions affecting the environmental assessment of the site can vary with time and that the conclusions and recommendations set out in this report are time sensitive. The client, and any other party using this report with the express written consent of the client and GW SOLUTIONS, also acknowledge that the conclusions and recommendations set out in this report are based on limited observations and testing on the area or subject site and that conditions may vary across the site which, in turn, could affect the conclusions and recommendations made. The client acknowledges that GW SOLUTIONS is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the client.

2.1 INFORMATION PROVIDED TO GW SOLUTIONS BY OTHERS

During the performance of the work and the preparation of this report, GW SOLUTIONS may have relied on information provided by persons other than the client. While GW SOLUTIONS endeavours to verify the accuracy of such information when instructed to do so by the client, GW SOLUTIONS accepts no responsibility for the accuracy or the reliability of such information which may affect the report.

3.0 LIMITATION OF LIABILITY

The client recognizes that property containing contaminants and hazardous wastes creates a high risk of claims brought by third parties arising out of the presence of those materials. In consideration of these risks, and in consideration of GW SOLUTIONS providing the services requested, the client agrees that GW SOLUTIONS’s liability to the client, with respect to any issues relating to contaminants or other hazardous wastes located on the subject site shall be limited as follows:

(1) With respect to any claims brought against GW SOLUTIONS by the client arising out of the provision or failure to provide services hereunder shall be limited to the amount of fees paid by the client to GW SOLUTIONS under this Agreement, whether the action is based on breach of contract or tort;

(2) With respect to claims brought by third parties arising out of the presence of contaminants or hazardous wastes on the subject site, the client agrees to indemnify, defend and hold harmless GW SOLUTIONS from and against any and all claim or claims, action or actions, demands, damages, penalties, fines, losses, costs and expenses of every nature and kind whatsoever, including solicitor-client costs, arising or alleged to arise either in whole or part out of services provided by GW SOLUTIONS, whether the claim be brought against GW SOLUTIONS for breach of contract or tort.

4.0 JOB SITE SAFETY

GW SOLUTIONS is only responsible for the activities of its employees on the job site and is not responsible for the supervision of any other persons whatsoever. The presence of GW SOLUTIONS personnel on site shall not be construed in any way to relieve the client or any other persons on site from their responsibility for job site safety.

5.0 DISCLOSURE OF INFORMATION BY CLIENT

The client agrees to fully cooperate with GW SOLUTIONS with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The client acknowledges that in order for GW SOLUTIONS to properly provide the service, GW SOLUTIONS is relying upon the full disclosure and accuracy of any such information.

6.0 STANDARD OF CARE

Services performed by GW SOLUTIONS for this report have been conducted in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Engineering judgement has been applied in developing the conclusions and/or recommendations provided in this report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of this report.

7.0 EMERGENCY PROCEDURES

The client undertakes to inform GW SOLUTIONS of all hazardous conditions, or possible hazardous conditions which are known to it. The client recognizes that the activities of GW SOLUTIONS may uncover previously unknown hazardous materials or conditions and that such discovery may result in the necessity to undertake emergency procedures to protect GW SOLUTIONS employees, other persons and the environment. These procedures may involve additional costs outside of any budgets previously agreed upon. The client agrees to pay GW SOLUTIONS for any expenses incurred as a result of such discoveries and to compensate GW SOLUTIONS through payment of additional fees and expenses for time spent by GW SOLUTIONS to deal with the consequences of such discoveries.

8.0 NOTIFICATION OF AUTHORITIES

The client acknowledges that in certain instances the discovery of hazardous substances or conditions and materials may require that regulatory agencies and other persons be informed and the client agrees that notification to such bodies or persons as required may be done by GW SOLUTIONS in its reasonably exercised discretion.

9.0 OWNERSHIP OF INSTRUMENTS OF SERVICE

The client acknowledges that all reports, plans, and data generated by GW SOLUTIONS during the performance of the work and other documents prepared by GW SOLUTIONS are considered its professional work product and shall remain the copyright property of GW SOLUTIONS.

10.0 ALTERNATE REPORT FORMAT

Where GW SOLUTIONS submits both electronic file and hard copy versions of reports, drawings and other project-related documents and deliverables (collectively termed GW SOLUTIONS's instruments of professional service), the Client agrees that only the signed and sealed hard copy versions shall be considered final and legally binding. The hard copy versions submitted by GW SOLUTIONS shall be the original documents for record and working purposes, and, in the event of a dispute or discrepancies, the hard copy versions shall govern over the electronic versions. Furthermore, the Client agrees and waives all future right of dispute that the original hard copy signed version archived by GW SOLUTIONS shall be deemed to be the overall original for the Project. The Client agrees that both electronic file and hard copy versions of GW SOLUTIONS's instruments of professional service shall not, under any circumstances, no matter who owns or uses them, be altered by any party except GW SOLUTIONS. The Client warrants that GW SOLUTIONS's instruments of professional service will be used only and exactly as submitted by GW SOLUTIONS. The Client recognizes and agrees that electronic files submitted by GW SOLUTIONS have been prepared and submitted using specific software and hardware systems. GW SOLUTIONS makes no representation about the compatibility of these files with the Client's current or future software and hardware systems.