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Mapping the Likelihood of Flowing Artesian Conditions in the Okanagan Basin and Fraser Valley, British Columbia

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Cover Photograph: Flowing well in Comox Valley, courtesy of Jim Fyfe, Fyfe Well & Water Services.

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EXECUTIVE SUMMARY

Flowing wells, also referred to as flowing artesian wells, are a known problem in many regions of the Province of British Columbia (B.C.), particularly in the Okanagan Basin and Fraser Valley. Flowing wells have the potential to be costly to drill especially when the possibility of encountering flowing artesian conditions is not known ahead of time. Additionally, when left to flow uncontrolled, flowing wells can contribute to water security concerns such as groundwater depletion. Unfortunately, land owners (and some drillers) are generally unaware of the risks of flowing wells. Moreover, apart from local knowledge on the part of well drillers, the risk of drilling a flowing artesian well in different regions of the province is largely unknown or not fully appreciated.

The purpose of this study was to determine the likely areas and extent of flowing artesian conditions in the Okanagan Basin and Fraser Valley and identify factors influencing the occurrence of flowing artesian conditions. These study areas are some of the most densely populated areas in the province and have some of the largest proportions of flowing wells relative to non-flowing wells. The project involved:

1) Characterizing the spatial distribution of known occurrences of flowing wells in the Okanagan Basin and Fraser Valley;
2) Using available spatial information (i.e., geological and soils maps, topography, groundwater data) in conjunction with the scientific understanding of hydrogeological controls on flowing wells to map the likelihood of occurrence of flowing artesian conditions in these two regions;
3) Examining the specific nature of flowing conditions in select case study areas;
4) Assisting the B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) in conducting inspections in the Fraser Valley and the Okanagan to document current conditions of identified flowing wells and making suggestions to government for promoting compliance; and
5) Preparing an information package to support decision-making, including this technical report, digital maps showing the likelihood of occurrence of flowing artesian conditions in each study area, and providing guidance to FLNRORD for developing area-specific advisories for land owners and water well drillers.

The study employed a range of techniques to explore flowing well occurrence in the two study areas.

Occurrence mapping was used to simply identify the locations of known flowing wells, as reported in GWELLS, and examine where these wells are occurring from a hydrogeological perspective. Findings of the occurrence mapping suggest that in the Okanagan Basin, both flowing and non-flowing wells have higher occurrences in the valley bottoms compared to the higher elevations. Non-flowing wells are relatively evenly distributed throughout the valley, while flowing wells are more heavily clustered in the central and northern Okanagan Basin, and are associated with confined, unconsolidated aquifers. Flowing wells tend to occur wherever non-flowing wells occur, with few exceptions, most notably north of Osoyoos in the southern portion of the basin where flowing wells occur sparsely. While the flowing wells are concentrated in the Okanagan valley, there are occurrences of flowing wells at higher elevation.

In the Fraser Valley, non-flowing wells occur extensively throughout the study area. Flowing wells occur sporadically throughout the Fraser Valley, but the majority are clustered in the low-lying areas within the Township of Langley and Surrey (immediately west of the Township of Langley municipal boundary). The majority of these clustered wells were determined by Carmichael (2011) to occur in Aquifer 58, the Nicomekl-Serpentine Aquifer (confined, unconsolidated aquifer); however, some of the clustered wells occur outside of the Aquifer 58 boundary.

Multi-criteria analysis (MCA) was used to evaluate factors relating to the occurrence of flowing wells. The analysis was carried out in a Geographic Information System (GIS) by employing raster tools in combination with statistics.

The results of the MCA were used to map the likelihood of flowing artesian conditions in three hydrogeological contexts: Okanagan bedrock, Okanagan unconsolidated and Fraser Valley unconsolidated. A range of spatially varying factors that are potentially related to the occurrence of flowing wells were considered, including:

- Elevation
- Slope
- Topographic Curvature
- Flow Accumulation (i.e., uphill contributing area)
- Topographic Wetness Index (TWI)
- Mapped Lineaments associated with different sets of regional fault and fracture zones
- Soil Drainage
- Soil Texture
- Presence of Confining Unit, and
- Stream Proximity.

Each hydrogeologic context had different factors that were applicable and determined to be statistically significant in influencing the occurrence of flowing artesian conditions. These factor maps are provided in Appendix B. While there were some commonalities, such as slope having one of the highest achieved significance levels in each hydrogeologic context, the opposite was also true, whereby some factors were only statistically significant in one hydrogeologic context (i.e., curvature in the bedrock context) or a factor that had a higher weight in one context relative to another (i.e., unconsolidated and bedrock contexts). For example, flow accumulation (i.e., uphill contributing area) was determined to be one of the most significant factors in the Okanagan bedrock and one of the least significant factors in the unconsolidated contexts.

Three maps were produced that show where flowing artesian conditions are ‘more likely than not’ to occur. The Okanagan bedrock MCA map is shown in Figure 14; the Okanagan unconsolidated MCA map is shown in Figure 17, and the Fraser Valley unconsolidated MCA map is shown in Figure 21. The MCA maps visually appear to accurately map flowing artesian conditions better when flowing wells are clustered and when there are more data points. The statistical method used to validate the maps indicated that the MCA maps accurately determined the extent of flowing artesian conditions in each hydrogeologic context. All maps produced in the MCA analysis met the statistical threshold set (a minimum Wilcoxon Test significance level of 15%). Importantly, all of the maps have areas where flowing artesian conditions are ‘more likely than not’, but these areas do not have any (or few) known flowing wells. The absence of flowing wells in these areas does not necessarily indicate that the maps are incorrect, as flowing wells may just not have been drilled yet.

The main utility of the MCA maps and the percent frequencies graphs is that they identify areas where flowing artesian conditions are ‘more likely than not’ to be encountered, even though flowing wells can occur across the entire study area for each hydrogeologic context. It is important to note that these regional-scale maps do not indicate any locations where it is impossible for flowing wells to occur or any locations where flowing wells are guaranteed to occur, only where they are ‘more likely than not’ to occur.

Site-specific case studies of flowing artesian conditions were carried out in Naramata (bedrock context), and South Vernon, Armstrong, and Aquifers 58 and 33 in Langley (unconsolidated contexts). These case studies indicate that the MCA maps accurately determine the extent of areas where flowing artesian conditions are ‘more likely than not’ to occur at local scales.

New (or modified) well drilling advisories are recommended for each of the following areas. The rationale for the area-specific advisories is provided in the respective subsections in Section 6.0. Details on the recommended advisories are provided in Section 7.4:

- The Naramata area for drilling in bedrock.
- Potentially a region-wide advisory or general provincial level guidance for drilling in bedrock in the Okanagan.
- The Armstrong area of the Okanagan.
- Aquifer 33 in the Fraser Valley, but perhaps only highlighting the western portion of the aquifer where the change in topography results in flowing artesian conditions.
- The existing advisory for Surrey and Langley (Aquifer 58) could be modified to exclude the highlands between the Nicomekl and Serpentine valleys. This advisory could also potentially be modified to include Aquifer 33 as flowing wells are in the immediate vicinity.

Well drilling advisories do not need to be limited to those recommended above. This study focused on specific areas that are representative of flowing artesian conditions being ‘more likely than not’ in each hydrogeologic context. However, areas mapped as ‘more likely than not’ occur in each hydrogeologic context in other areas, and these other areas warrant more detailed examination.

The maps produced as part of this study can provide guidance for well drillers and groundwater consultants. The maps can be used in conjunction with known flowing (and non-flowing) well locations to inform decisions around drilling and preparation, well design, as well as cost. As an additional tool, the information on the map alongside professional judgement can be used to assess the likelihood of flowing artesian conditions. Importantly, the maps should not be relied upon as the sole information source due to various limitations (see Section 8.2). The maps are simply meant as one tool to aid in the decision-making process.

The maps may also be used to inform any future regulations regarding drilling authorizations under the *Water Sustainability Act* and *Drinking Water Protection Act* in local areas that are mapped as ‘more likely than not’ for encountering flowing artesian conditions.

Finally, the methods developed in this study can be applied in other regions where flowing wells are known to occur. The approach can be adapted to accommodate the factors available for the area. For example, lineament datasets may not be available in all regions where flowing bedrock wells are encountered, but the methodology can still be implemented with the datasets that are available.

CONTENTS

1. INTRODUCTION

Flowing wells, also referred to as flowing artesian wells, are a known problem in many regions of the Province of British Columbia (B.C.), particularly in the Okanagan Basin and Fraser Valley. Allowed to flow uncontrolled, these wells can eventually reduce the long-term sustainability of the aquifer, leading to reduced water yield from wells and springs, and potentially reduce natural groundwater discharge to streams which can impact aquatic habitat. An example of uncontrolled flow leading to reduced water yield is in the Semlin Valley near Cache Creek in the Interior of B.C. (Chapter 13.7, B.C. Ministry of Environment, 1993). Uncontrolled flow at the ground surface means that this water must be conveyed, in some cases un-naturally, into streams. The low oxygen content of the groundwater entering the stream may impact aquatic habitat. Moreover, flowing wells may lead to subsidence or sinkholes as evidenced by the recent flowing wells in the City of Vancouver (City of Vancouver, 2016; Lee, 2016) and Chetwynd in northeast B.C. (Province of B.C., 2017b). The result may be extensive property damage, impacts to infrastructure, loss of property value, and exorbitant costs to the property owner, as well as limiting the future use of the land. Unfortunately, land owners are generally unaware of the risks of flowing wells, and apart from local knowledge on the part of well drillers, the risk of drilling a flowing artesian well in different regions of the province is largely unknown or not fully appreciated.

The British Columbia GWELLS database contains records of many (but not all) wells drilled in the province. Prior to the enactment of the *WSA* in 2016, it was not mandatory for well records to be submitted to the Province and therefore many wells are not identified in GWELLS. This publicly accessible database is the primary source of information on groundwater in the province and is used by groundwater professionals (water well drillers, pump installers, consultants, government staff, academics) for mapping and characterizing groundwater in the province. Of the ~120,185 wells in the database (as of March 5, 2021), 2,991 wells have been identified as flowing artesian (~2.5%) – one flowing well (in Surrey) has a reported flow rate of 1700 gallons per minute. To put this into context, an Olympic sized swimming pool (2,500,000 L) would be filled in just over 6 hours. To date, however, there has been no systematic assessment of existing flowing wells in the province. Where are these wells? What are the local geological characteristics that have created a suitable setting for flowing wells? Besides known locations of flowing wells, where might we find other aquifers where flowing wells might be drilled? And how might well construction standards be improved to stop or control flowing wells? While we understand, in principle, what geological/hydrogeological conditions are associated with artesian aquifers, we currently lack knowledge of specific conditions that increase the risk of encountering flowing artesian conditions during drilling in different areas of the province.

This project aims to fill these knowledge gaps, and disseminate that knowledge to decision-makers, practitioners and the general public through the development of a more comprehensive understanding of the factors controlling where flowing wells may exist and where there is greater likelihood of flowing wells. The main objectives of the study include:

1) Characterizing the spatial distribution of known occurrences of flowing wells in the Okanagan Basin (Allen, 2017 and updated in this report) and Fraser Valley. These two study areas were chosen as the study areas for three main reasons: i) they represent different physiographic and hydrogeological settings; ii) they have the highest density of wells in the province; and iii) they have high numbers of flowing wells.
2) Using available spatial information (i.e., geological and soils maps, topography, groundwater data) in conjunction with scientific understanding of hydrogeological controls on flowing well occurrence to:

a. Develop conceptual models of flowing artesian conditions in different hydrogeological contexts (bedrock and unconsolidated aquifers);
b. Identify the statistically significant factors (e.g., slope, aquifer confining conditions) associated with flowing wells; and
c. Develop a geostatistical approach based on Multi-Criteria Analysis (MCA) for mapping the likelihood of flowing conditions specific to each hydrogeological context in the two study areas.

3) Examining through case studies the hydrogeological conditions (supported by geological models) and the specific nature of flowing conditions.
4) Preparing an information package to support decision-making, as well as assisting the B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) in documenting current conditions of flowing wells during inspections in the Fraser Valley and Okanagan Basin; making suggestions to government for promoting compliance; and providing guidance to FLNRORD for developing area-specific advisories for land owners and practitioners.

This report is organized as follows:

- Section 1 introduces the report and lists the main objectives.
- Section 2 provides a historical background on the physical hydrogeological conditions that can lead to flowing wells, along with an overview of approaches used to map flowing artesian conditions.
- Section 3 summarizes the results of the high-level analysis of the occurrence of flowing wells in the Okanagan Basin and Fraser Valley.
- Sections 4 and 5, describe the approach used (i.e., the MCA) and the results of mapping likelihood of flowing artesian conditions in the Okanagan Basin and Fraser Valley, respectively (Appendix A provides some details on the MCA approach, which are described more fully in Johnson (2021), and Appendix B shows the various factor maps).
- Section 6 illustrates through case study examples the occurrence of flowing artesian conditions in bedrock and unconsolidated hydrogeological contexts.
- Section 7 provides suggestions to FLNRORD and the B.C. Ministry of Environment and Climate Change Strategy (ENV) to support continued regulatory compliance and enforcement efforts, as well as issuing area-specific advisories on flowing artesian conditions. This section also includes a summary of the results of inspections of 22 wells carried out between March 9 and 12, 2020 by FLNRORD staff in the Surrey-Langley area and observed by Brynje Johnson.
- Section 8 offers some general conclusions and recommendations.

The project team (Brynje Johnson, MSc student at SFU, Diana Allen and Mike Wei) participated in three B.C. Ground Water Association (BCGWA) events: 1) the Regional BCGWA Fraser Valley meeting in 2018; 2) the BCGWA Annual Conference in 2019; and 3) the BCGWA Conference in 2021. At each event, there was an opportunity to engage with well drillers and professionals to glean practical knowledge surrounding cases of artesian wells. At the BCGWA 2019 meeting, locations of flowing wells that drillers were aware of were identified and plotted on hard copy maps.

2. BACKGROUND ON FLOWING ARTESIAN CONDITIONS

2.1 The Nomenclature of Artesian Conditions

The nomenclature surrounding artesian conditions varies throughout the literature. Frequently, the terms 'artesian' and 'flowing artesian' are used interchangeably to describe flowing artesian conditions in an aquifer or a well. However, a distinction should be made between the two. By definition, an *artesian* aquifer is one in which the hydraulic head (or potentiometric surface) lies above the top of the aquifer due to the presence of a confining layer (Freeze and Cherry, 1979). In an *artesian well*, the height of the water column is at least above the top of the aquifer, but not necessarily above the top of the well casing. Whereas in a *flowing artesian well*, the height of the water column is above the top of the well casing and thus results in water discharging from the well. Of course, the well casing can be extended to a sufficient height above ground surface to stop the flow. Thus, for practical purposes, flowing artesian conditions occur at any location where a well is drilled into an aquifer and the hydraulic head in the well exceeds the local ground surface elevation. It should be noted that wells may not be identified as 'flowing' by groundwater professionals (e.g., well drillers) if the water level is not above the top of casing because if the hydraulic head is below the top of casing it will not visually appear to be flowing. A well can also be drilled at a time when the groundwater level is below ground but rises above ground with the rise in seasonal groundwater level.

The term 'flowing artesian', while sometimes associated with aquifers, is more commonly associated with a well. Likewise, the terms 'flowing well' and 'flowing artesian well' are frequently used synonymously. In this report, the term 'flowing well' is used when referring to a well, and the term 'under flowing artesian conditions' is used when referring to an aquifer.

2.2 Conceptual Models for Flowing Conditions

There are two widely accepted models of hydrogeologic environments that can result in flowing artesian wells: geologically-controlled models and topography-controlled models (Freeze and Cherry, 1979). The term 'artesian' is by definition only applicable in the geologically-controlled model (confined aquifer), although it is also used in the literature when referring to flowing conditions in topography-controlled conditions (e.g., Wang et al., 2015). These two models are discussed below.

2.2.1 Geologically-Controlled Models

Geologically-controlled flowing artesian conditions are associated with confined aquifers. The most robust sources in the literature that define flowing artesian conditions in aquifers are also some of the oldest sources on the subject. Chamberlin (1885) defined the most well-known model of geologically-controlled artesian aquifers, identifying seven requisites necessary for the occurrence of artesian conditions and therefore flowing wells (Chamberlin, 1885):

1) A pervious stratum to permit the entrance and the passage of the water (aquifer);
2) A water-tight bed below to prevent the escape of the water downward (confining unit or aquitard below the aquifer);
3) A similarly impervious bed above the pervious stratum to prevent escape upward, for the water, being under pressure from the fountain-head, would otherwise find relief in that direction (confining unit or aquitard above the aquifer);
4) An inclination of these beds, so that the edge at which the waters enter will be higher than the surface at the well;
5) A suitable uphill exposure of the edge of the porous stratum (where the aquifer is not confined), so that it may take in a sufficient supply of water;

6) An adequate rainfall precipitation to furnish this supply; and
7) An absence of any escape for the water at a lower level than the surface at the well.

These conditions define a typical sloping confined aquifer which creates flowing artesian conditions in the down-dip region of the aquifer (Figure 1). The potentiometric surface is above ground surface at the location of the flowing well. The level to which the water rises in the confined aquifer is controlled by the elevation of the water table in the confined unit in the recharge area (where the aquifer is not yet confined). Flowing artesian conditions would occur everywhere the potentiometric surface is above ground surface.

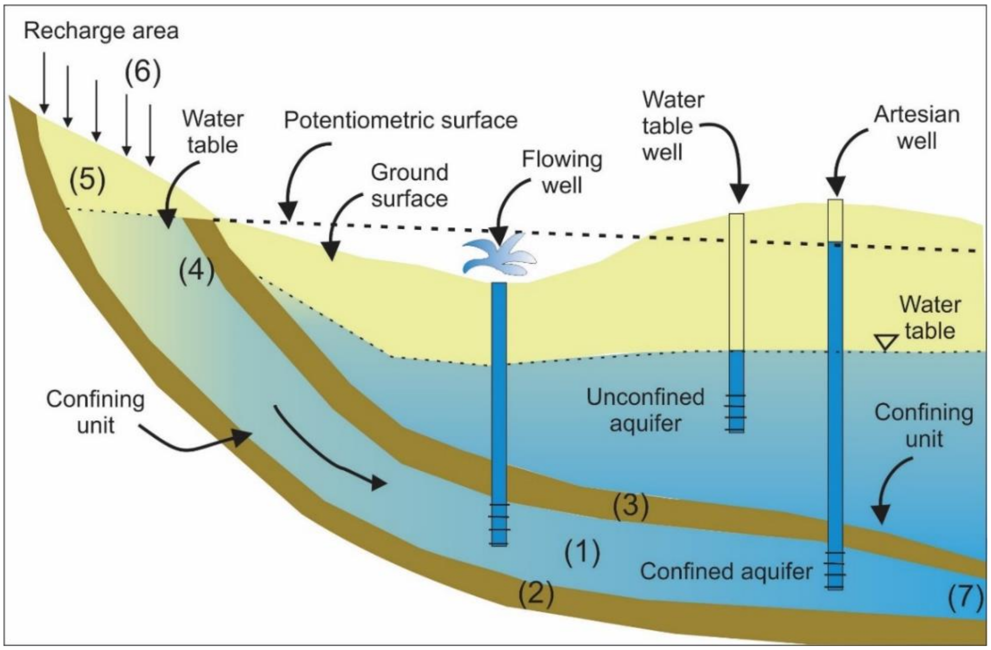

Figure 1: Geologically-controlled artesian conditions which result in flowing wells due to the potentiometric surface of the confined aquifer above ground surface at the location of the flowing well (modified from Todd, 1959). Numbers in brackets relate to the list above.

Chamberlin (1885) noted that the 'pervious stratum' defined in the first requisite does not need to be a typical porous medium (i.e., granular), but can be fissured and channelled beds, although he suggested that their occurrence is much less likely. Figure 2 illustrates a conceptual geologically-controlled model in which the substrate is fractured bedrock. Fracture pathways intersected by the flowing well are connected to the recharge area. The fractures are effectively confined by the surrounding bedrock matrix, resulting in the potentiometric surface associated with the deep fracture in the well being above ground surface.

Fuller (1908) proposed a more expansive view on the characteristics of the water reservoir, giving multitudes of examples, such as vein contacts, cleavage planes, foliation, schistosity planes, etc. that form the water reservoir. Fuller (1908) also noted several other 'modifying factors' that contribute to artesian conditions in different ways. For example, barometric pressure, temperature, rock density and rock pressure, porosity and size of pores or openings, topographic conditions, and conditions of leakage.

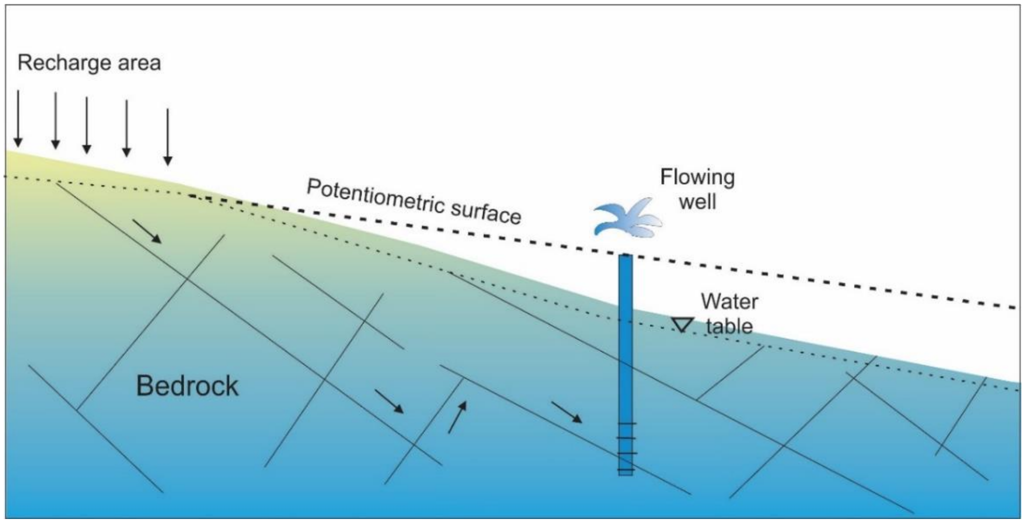

Figure 2: A fractured bedrock aquifer illustrating flow paths along fractures that connect to a recharge area at higher elevation to result in the potentiometric surface above ground surface at the location of the flowing well (modified from Casewell, 1987).

2.2.2 Topography-Controlled Models

While geological conditions are generally better known as controlling conditions for flowing (artesian) wells, Freeze and Cherry (1979) assert that topography is the primary control. In both of the conceptual models (the confined aquifer in Figure 1 and the fractured bedrock aquifer in Figure 2) shown above, some topographic relief is needed to generate the high hydraulic head at depth. Indeed, Freeze and Cherry (1979) point out the that conditions that create geologically-controlled artesian conditions are not particularly common despite the widespread use of the geologically-controlled model for explaining flowing wells. Any hydrogeologic system that leads to hydraulic head values in an aquifer exceeding ground surface elevation can result in flowing wells.

Topography-controlled flowing wells can essentially occur anywhere the hydraulic head at depth (where the well is screened) is higher than the ground elevation at the well (Figure 3). Areas where upward flow is common include topographic depression, such as valley bottoms, where groundwater discharge occurs. Topography-controlled flowing wells are commonly associated with unconfined aquifers, and therefore are not strictly defined by the presence or absence of specific geological units, such as confining units. Figure 3 shows a typical topography-controlled flowing well completed within an unconfined aquifer. Here the flowing well is situated in a groundwater discharge zone associated with a surface water body in a topographically low area. Topographic relief is the reason for the common occurrence of flowing artesian conditions in valleys.

2.2.3 Combined Controls on Flowing Artesian Conditions

In the geologically-controlled model it is the combination of the confined aquifer and a water source at higher elevation (topography) that creates flowing artesian conditions in the aquifer at lower elevation. Whereas in the topography-controlled model, it is the topographic relief primarily that creates upward vertical gradients and a discharge zone. These models are represented as being mutually exclusive in the literature, but they really represent end members of a spectrum of controls on flowing artesian conditions. Therefore, combinations of geological and topographic factors are important to consider when artesian conditions are of concern.

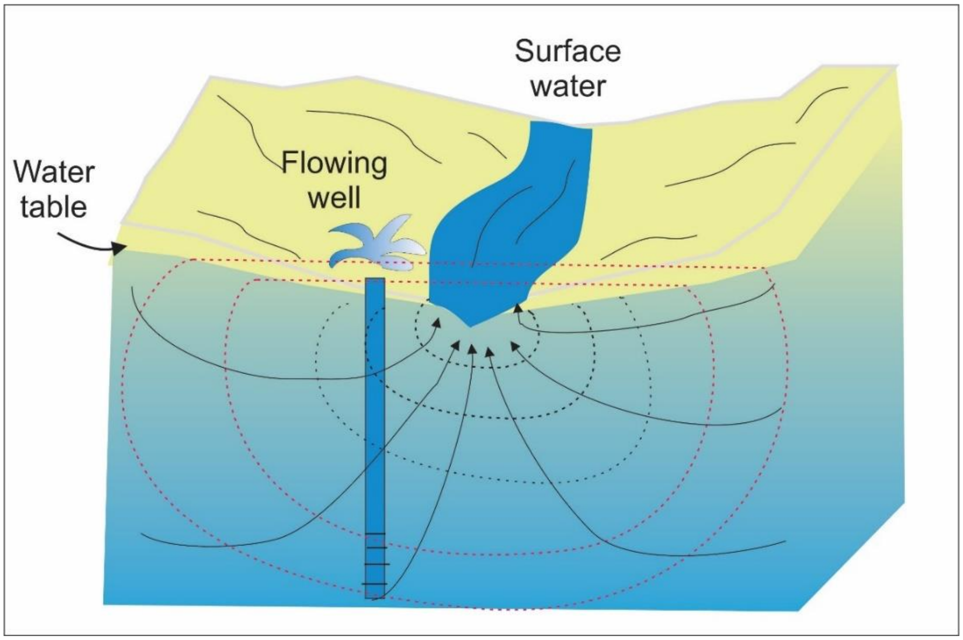

Figure 3: Flowing artesian conditions in topography-controlled unconfined aquifer (modified from Gaber, 2005). The two equipotential lines intersected by the well screen are associated with hydraulic head values above ground surface, as illustrated by the red horizontal dashed lines above the surface. Adapted from B.C. Ministry of Environment, no date).

2.3 Mapping Flowing Artesian Conditions

Two main methods are used for estimating the extent of flowing artesian conditions. The first is simply mapping the known occurrence of flowing artesian conditions (here referred to as occurrence mapping). The majority of mapping done by jurisdictions can be defined as occurrence mapping. The second, less common type of mapping is predictive mapping, where the likelihood of flowing artesian conditions is mapped based on the known occurrence of flowing wells and then extrapolated to define larger areas based on certain parameters, which could vary depending on the specific study, but usually include parameters such as topography, water levels, slope, depth and the aquifer that the well would be screened in.

2.3.1 Occurrence Mapping

Jurisdictions that use the occurrence mapping system typically provide the data through a web-based geographic information system (GIS). Some examples are below.

British Columbia

B.C. has conducted both occurrence and potential mapping of flowing artesian conditions. Occurrence mapping uses water well information in the provincial GWELLS database that can be accessed through iMapBC (Province of B.C., no date a). Specifically, iMapBC includes a provincial data layer of known flowing wells. Additionally, the Province of B.C. also produces well drilling advisories for areas of known flowing artesian conditions. For example, the Vancouver well drilling advisory shows an area of potential artesian flow (a form of predictive mapping) based on four known flowing wells (Province of B.C., 2017a). The spatial data are accessible using VanMap (a GIS interface from ArcMap). All well drilling advisories for B.C. are posted on the Flowing Artesian Conditions Advisories webpage (Province of B.C., no date b).

Michigan

Michigan has an occurrence mapping system that is publicly available. Michigan's well database (Wellogic), maintained by Michigan's Department of Environmental Quality (State of Michigan, 2022), contains data specific to artesian wells (although not necessarily flowing wells). Michigan also conducted the Michigan Groundwater Inventory and Mapping Project; artesian aquifers were not specifically mapped in the project, but wells through Wellogic were considered (Michigan State University, n.d.).

Florida

Florida has maps of flowing artesian conditions within the Upper Floridian Aquifer; however, these maps are relegated to old paper maps from the 1900s. It is currently unknown whether the artesian conditions are of the same extent as they were when the maps were originally published (State of Florida Department of Agriculture, 1931). Groundwater usage has increased in Florida over the past couple decades due to increasing population, and this increase in groundwater use could have easily resulted in reduced flowing artesian conditions, but it is unknown if this is the case. Florida maintains a GIS (and spreadsheet) with well data (Florida Department of Environmental Protection, 2014), although there is no designation for artesian wells in the open source data.

The St. Johns District in Florida had developed annual potentiometric surface maps from 2000 to 2009, with the most complete data from 2006-2009 (United States Geological Survey (USGS), 2013). The maps were not intended for mapping artesian conditions, but the mapped potentiometric surface represents the Upper Floridan Aquifer in the St. Johns District. These data have the potential to be cross referenced with topographic data to identify areas of artesian flow but are not currently being used in that way. Parts of Florida have been modelled; for example, the east coast of the Floridan Aquifer System (FAS) (Golder Associates Inc., 2008). While the purpose of the modelling was not to predict or infer artesian flow specifically, the study included a mapping component specific to identifying artesian conditions. There are several other modelling projects of this type in other regions of Florida.

2.3.2 Predictive Mapping

Predictive mapping of flowing artesian conditions considers factors such as elevation, slope, profile curvature, aspect, topographic wetness index (TWI), as potential predictors of flowing artesian conditions. For example, Al-Abadi and Shahid (2016) used a machine learning algorithm and a GIS to delineate a flowing artesian zone in the southern desert of Iraq. They explored a variety of factors and found that elevation, well depth, distance to Euphrates River, distance to Abu-Jir fault, aquifer groups, and groundwater heads are the most important predictors, while the slope, curvature, aspect, TWI, and standardized precipitation index (SPI) have less influence in delineating the groundwater flowing well potential in the study area.

2.3.3 Approaches Used in this Study

This study uses both occurrence mapping and predictive mapping of flowing artesian conditions. The occurrence mapping was carried out at the outset of the project to gain a high-level understanding of the distribution of flowing wells in each study area, the Okanagan Basin and the Fraser Valley. The occurrence mapping is described in Section 3.

A predictive mapping approach was developed and implemented to map the likelihood of flowing artesian conditions in the two study areas. Conceptual models of flowing artesian conditions were considered in two different hydrogeological contexts (fractured bedrock and unconsolidated aquifers) in order to identify potential factors that might influence the occurrence of flowing artesian conditions. Within each hydrogeological context, the statistical significance of these different factors (e.g., slope, confining conditions, distance from streams and fracture zones) were explored. Then, a geostatistical approach based on Multi-Criteria Analysis (MCA) was developed for predicting the likelihood of flowing conditions specific to each hydrogeological context in the two study areas. The predictive mapping approach is described in Section 4.

3. OCCURRENCE MAPPING OF FLOWING ARTESIAN CONDITIONS

3.1 Okanagan Basin

The Okanagan Basin is located in south-central B.C. The basin trends north-south, spanning from just north of the City of Armstrong to Osoyoos at the Canada-USA border. Within B.C., the basin is 200 km in length and approximately 8000 km^2 in area (Figure 4). Okanagan Lake, extending throughout much of the valley bottom, is flanked with mountains on east and west with elevations ranging from 300 masl to 1800 masl. Population densities are higher in the valley bottom as is water well occurrence.

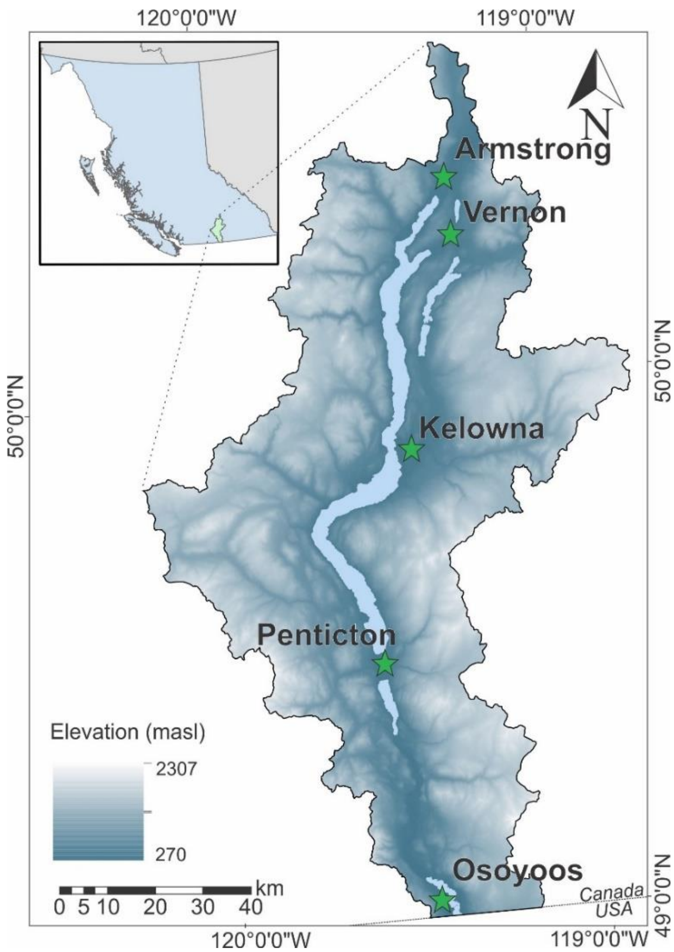

Figure 4: Digital Elevation Model of the Okanagan Basin with major cities identified.

The Okanagan valley fill represents glacial deposits from the late Pleistocene when the majority of the unconsolidated deposits on the valley bottom accumulated (Nasmith, 1962). At least two glacial and interglacial intervals have been identified in the Okanagan valley (Fulton and Smith, 1978). These have resulted in four main depositional environments in the Okanagan valley; sub glacial fluvial, glacial lacustrine, alluvial fan, and channel (Vanderburgh and Roberts, 1996).

The bedrock in the Okanagan Basin is characterized by a crustal shear zone called the Okanagan Valley Fault System (Tempelman-Kluit and Parkinson, 1986). The Okanagan Valley Fault Zone is characterised by a detachment fault running under Okanagan Lake as well as extension faults cutting through the bedrock (Tempelman-Kluit and Parkinson, 1986; Johnson, 2006). The bedrock in the Okanagan Basin is generally crystalline and highly consolidated but is sufficiently fractured to allow for groundwater flow.

As part of a preliminary phase of this project, the occurrence of flowing wells in the Okanagan Basin was examined (Allen, 2017). The information on flowing well occurrence was updated for this final report. As of June, 2020, there were 8004 reported[1] wells in the Okanagan Basin, 533 (~6.7%) of which were reported to be flowing wells (Figure 5). Both flowing and non-flowing wells have higher occurrences in the valley bottoms. Non-flowing wells are relatively evenly distributed throughout the valley, while flowing wells are more heavily clustered in the central and northern Okanagan Basin. Flowing wells tend to occur wherever non-flowing wells occur, with few exceptions, most notably north of Osoyoos in the southern portion of the basin where flowing wells occur sparsely despite the high occurrence of non-flowing wells.

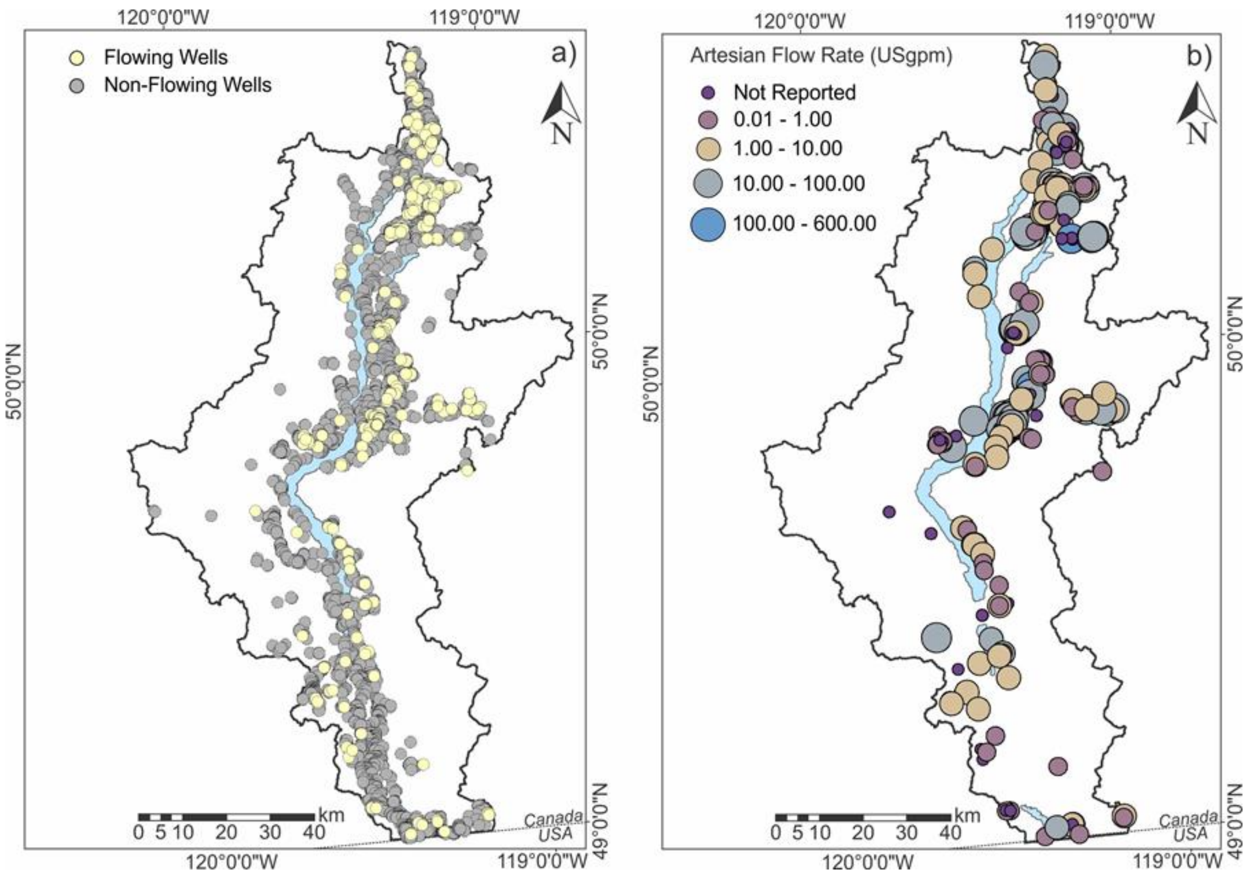

Figure 5: a) Flowing and non-flowing wells in the Okanagan Basin b) Flow rates of flowing wells reported in US gallons per minute (USgpm).

[1] Reported in GWELLS. Importantly, the actual number of wells may be higher due to unreported wells.

Reported flow rates[2] range up to 600 US gallons per minute (gpm) (although some rates may in fact be in Imperial gpm) and these rates have not been field verified. Wells without reported flow rates make up the largest category in Table 1 (43.2%). Approximately 23.5% of flowing wells are drilled in bedrock, while 66.8% are screened in unconsolidated sediments, and the remaining 9.8% are drilled in an unknown lithology (Figure 6). Due to this distribution of aquifer material type, flowing wells in the Okanagan Basin are separated into two hydrogeologic contexts for this study, bedrock and unconsolidated. While the flowing wells are concentrated in the Okanagan valley, there are occurrences of flowing wells at higher elevation.

There were two well-known flowing wells within/near the Okanagan valley. The first was the Coldstream well, drilled in 1965 at the Coldstream Ranch in the northeast of the study area. The flow rate was 600 USgpm. The well flowed for 50 years before it was successfully decommissioned (Beeby, 2015). The Westwold well was drilled more recently. It flowed at 500 USgpm before it was recently decommissioned (Province of B.C., 2018a; Western Water Associates Ltd., 2019).

Table 1: Reported flow rates and percent frequencies for flowing wells in the Okanagan Basin.

Reported Flow Rate (USgpm)	Frequency	% Frequency
Not Reported	230	43.2
0 – 1	80	15.0
1 – 10	124	23.3
10 – 100	89	16.7
100 – 1000	10	1.9

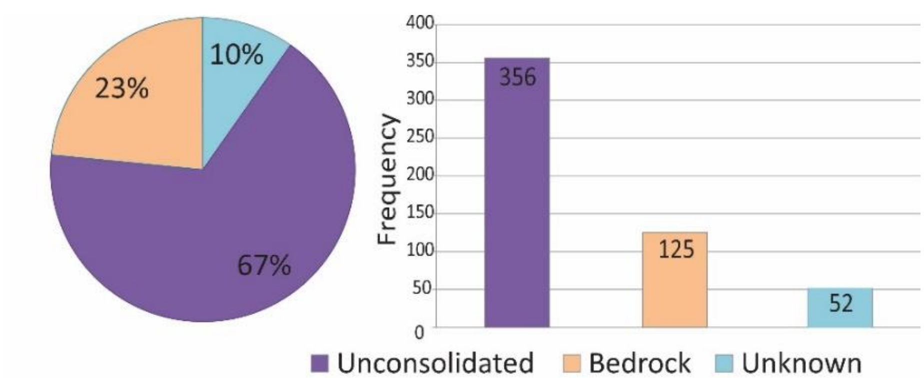

Figure 6: Aquifer lithology for flowing wells in the Okanagan Basin in percent (pie graph) and frequency (bar graph).

[2] Rates of 0.01 USgpm in GWELLS simply indicate flowing conditions are reported but no flow rate was measured.

3.2 The Fraser Valley

The Lower Fraser Valley (henceforth Fraser Valley) is located in southwest B.C. The Fraser Valley has low to moderate relief with elevations generally ranging from ~sea level to 150 metres above sea level (masl) (Clague et al., 1983). One notable exception is Sumas Mountain, which has an elevation upwards of 800 masl. High elevations represent the Fraser highlands and the edge of the Coast Mountains and the Cascade Mountains. The study area (~1800 km^2) encompasses only the valley bottom (Figure 7) and extends from Hope in the east to the Salish Sea in the west, and from the Pacific Ranges of the Coast Mountains in the north to Canada-USA border and the Cascade Mountains to the south. The study area excludes the surrounding high elevation areas along the edges of the valley because they have low population densities and few to no wells drilled.

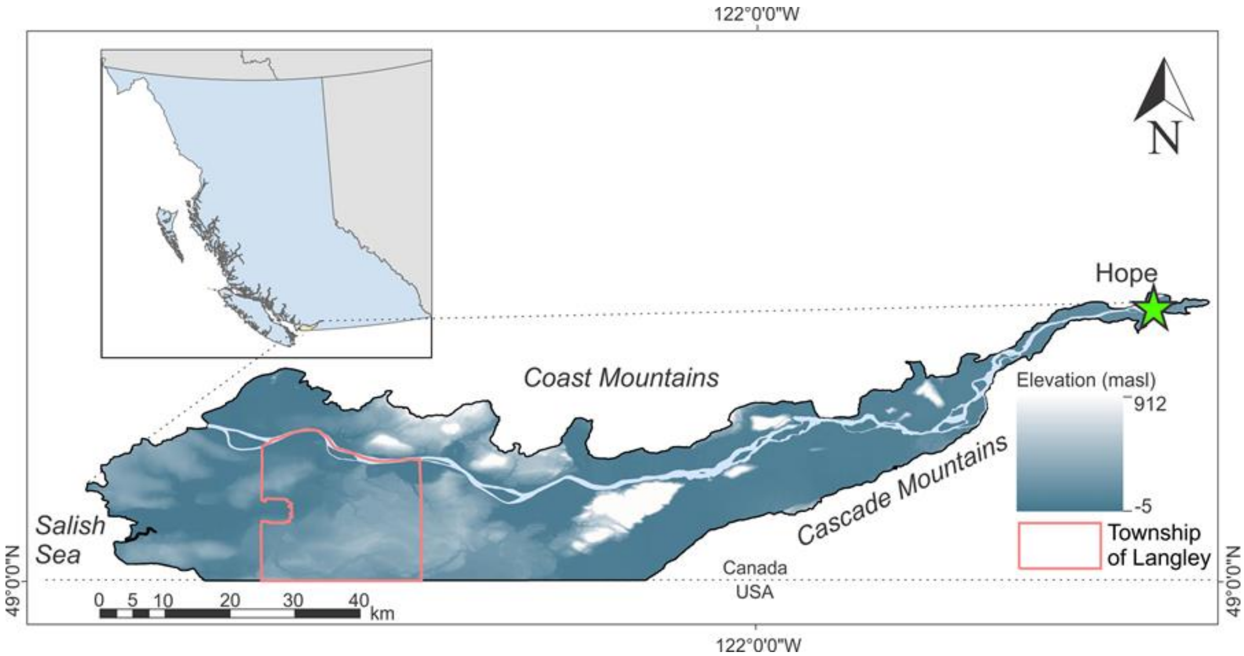

Figure 7: Digital Elevation Model of the Fraser Valley with the Township of Langley identified in red.

The aquifers in the Fraser Valley are made up almost exclusively of Quaternary deposits. These deposits are up to 300 m thick and are the result of the complex glacial and interglacial depositional history, consisting of at least three glaciations (Clague, 1994). Local fluctuations in relative sea level of up to 200 m, which were triggered by isostatic movements due to the retreating and advancing glaciers, were associated with periods of regression and transgression of the shoreline with respect to land (Armstrong, 1981). The sedimentary deposits consist of thick drift intervals bounded by glacial unconformities, non-glacial unconformities, and non-glacial deposits (Clague and Luternauer, 1983). The heterogeneous drift sequences are bound by unconformities from glacial erosion. Fluvial, marine, and mass wasting events were common during the interglacial period and also incised the glacial deposits throughout the Fraser Valley (Clague and Luternauer, 1983). Early Pleistocene glaciations are poorly preserved in the Quaternary stratigraphic record as they were eroded away during the most recent Fraser Glaciation in B.C. (Clague and Luternauer, 1983). Thus, the Fraser Glaciation (most recent major glaciation) had the largest impact on the deposits and current landscape (Clague, 1994).

There are 15,905 non-flowing wells reported in the Fraser Valley and 786 (~4.9%) flowing wells (Figure 8a). Non-flowing wells occur extensively throughout the study area and very few land parcels do not have wells drilled. Flowing wells occur sporadically throughout the Fraser Valley, but the majority are clustered in the low-lying areas within the Township of Langley (see Figure 8a) and Surrey (immediately west of the Township of Langley). The majority of these clustered wells were determined by Carmichael (2011) to be completed in Aquifer 58, the Nicomekl-Serpentine Aquifer; however, some of the clustered wells occur outside of the Aquifer 58 boundary.

The reported flow rates range up to 1800 USgpm (Figure 8b; Table 2). Flowing wells without reported flow rates have the highest frequency (341 wells; 43.4%) in Table 2. Flow rates between 1–10 USgpm are the most frequently reported values. Only 1% of the wells are drilled into bedrock, 83% are screened in unconsolidated sediments, and the remaining 16% are drilled in an unknown lithology (Figure 9). Due to the very low number of flowing wells completed into bedrock, flowing wells are only examined in the Fraser Valley for an unconsolidated context.

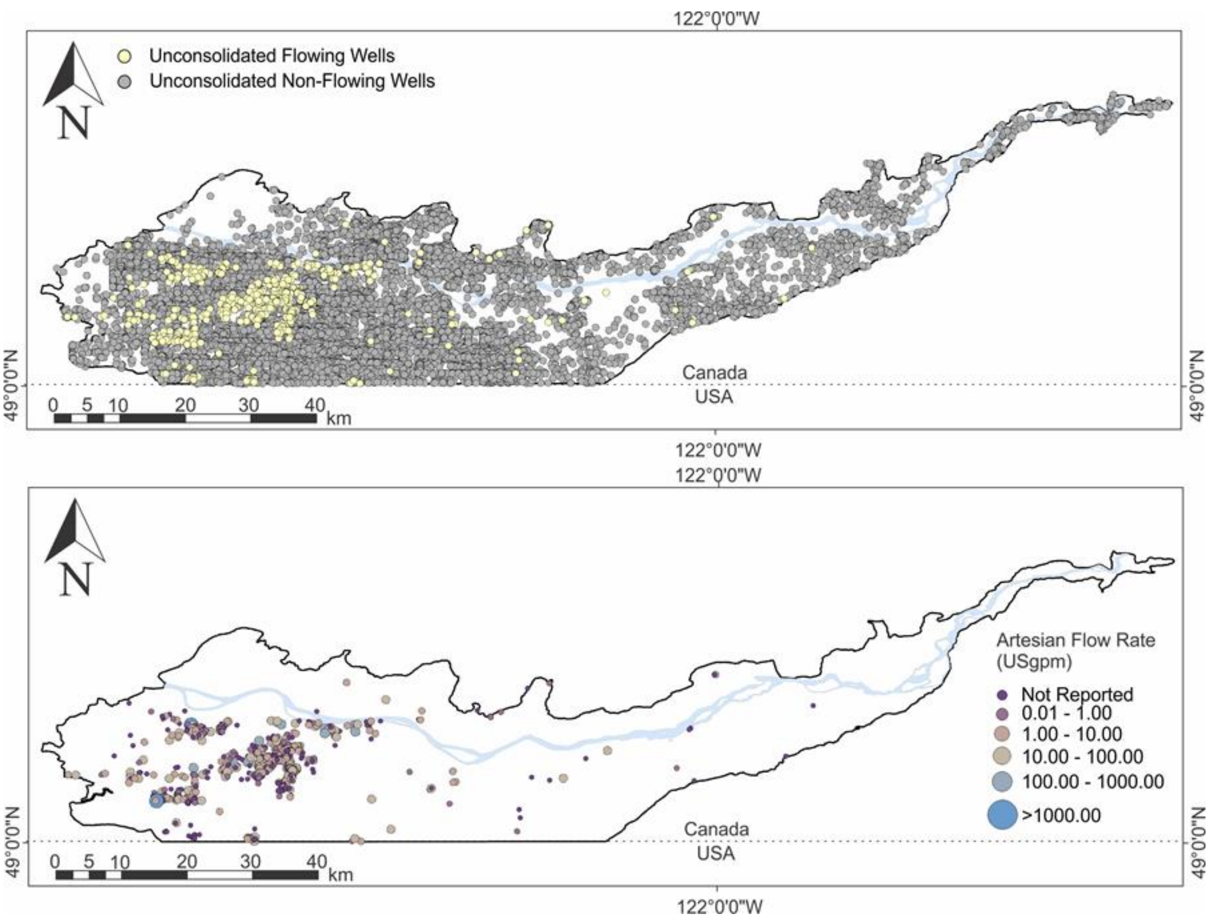

Figure 8: a) Flowing and non-flowing wells in the Fraser Valley b) Flow rates of flowing wells reported in US gallons per minute (USgpm).

Table 2: Reported flow rates and percent frequencies for flowing wells in the Fraser Valley.

Reported Flow Rate (USgpm)	Frequency	% Frequency
Not Reported	341	43.4
0 -1	130	16.6
1 -10	202	25.7
1 – 100	98	12.5
100 – 1000	12	1.5
> 1000	2	0.3

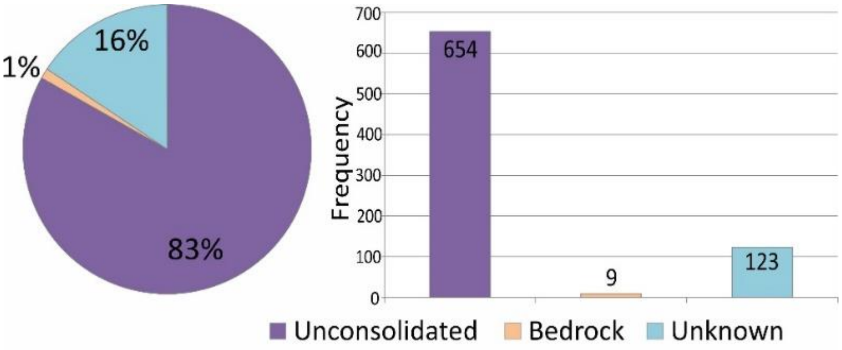

Figure 9: Aquifer lithology for flowing wells in the Fraser Valley in percent (pie graph) and frequency (bar graph).

4. PREDICTIVE MODELLING USING MULTI-CRITERIA ANALYSIS – METHODOLOGY

4.1 Overview

Multi-Criteria Analysis (MCA) has traditionally been applied as a decision-making technique and has gained popularity in many aspects of water management (Roozbahani et al., 2018; Rubio-Alaga et al., 2021). When applied in a GIS context, MCA can be used to answer questions that have a spatial component, such as land suitability for agriculture or identifying critical areas for wildlife protection (Malczewski and Rinner, 2015). The results of the MCA analysis are displayed on a map.

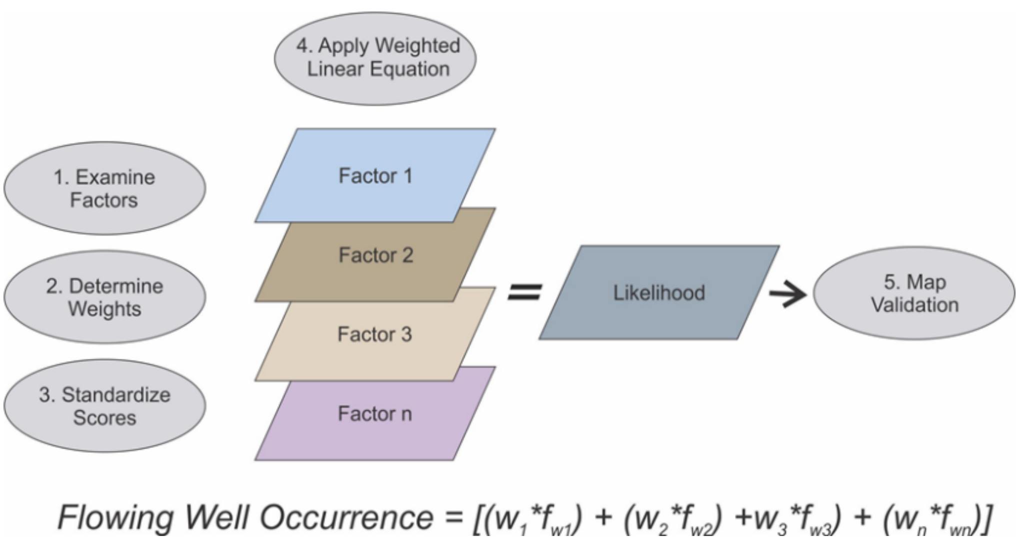

Figure 10: Overall stepwise approach for the Multi-Criteria Analysis.

In this study, MCA was used to evaluate factors relating to the occurrence of flowing wells to determine the spatial likelihood of encountering flowing artesian conditions during drilling. This raster-based approach involves constructing a linear weighted empirical equation that is applied to each raster cell in a series of steps outlined in Figure 10:

1. **Examine factors** – the spatial factors suspected to influence the occurrence of flowing artesian conditions are examined to determine which factors are statistically significant and will be used in the MCA. Factors are symbolized by f_{wi} in the Flowing Well Occurrence equation.

2. **Determine weights** – the weighting of each factor is determined, based on the statistical significance of the factor. Weights are symbolized as w_i in the Flowing Well Occurrence equation.
3. **Standardize scores** – the factors are standardized to a scale representing the likelihood of occurrence of flowing artesian conditions.
4. **Apply weighted linear regression** – the weighted linear equation is applied whereby the standardized and weighted factors are added together to produce the final MCA map showing likelihood of encountering flowing artesian conditions.
5. **Validate map** – the resulting map is validated using a series of Wilcoxon Rank Sum Tests.

Maps showing the likelihood of encountering flowing artesian conditions were prepared for three hydrogeological contexts:

1. bedrock wells in the Okanagan Basin,
2. wells in unconsolidated materials in the Okanagan Basin, and
3. wells in unconsolidated materials in the Fraser Valley.

Sections 4.2 – 4.7 provide an overview of which factors were considered for the MCA and ultimately how each factor was selected, standardized and weighted in the final MCA maps. Sections 4.8 – 4.10 describe the map classification and validation steps. Appendix A describes the data processing methods used for each step of Figure 10 in detail. ESRI ArcMap 10.6 was used for the spatial data analysis and integration, and MATLAB R2018a was used to perform the statistical analyses. The full-size factor maps for the Okanagan can be found in Appendix B and the full-size factors maps for the Fraser Valley can be found in Appendix C. Appendix D shows the percent frequency distributions for all three hydrogeological contexts. The final MCA maps are presented and discussed in Section 5. Section 6 explores three case study areas: Naramata in the Okanagan, Vernon Creek in the Okanagan, and Langley Township in the Fraser Valley.

4.2 Selection of Factors

An important first step for conducting a MCA is deciding which factors to use. Several spatial factors were identified that may influence the occurrence of flowing artesian conditions. Table 3 lists these potential factors, along with the data source used in the analysis. These factors were selected for examination based on 1) how they could potentially influence the occurrence of flowing artesian conditions in the two models (the geologically and topography-controlled models), 2) findings of previous studies on related topics (e.g., Al-Abadi and Shahid, 2016; Bystron, 2018), and 3) availability of data and adequate spatial extent throughout the study areas.

Each factor was examined by first processing the spatial data and then evaluating its significance as an indicator of flowing artesian conditions. In the following subsections, an overview of each factor is provided. Appendix A describes the workflow in detail.

4.2.1 DEM and DEM Derived Factors

Elevation, slope, curvature, flow accumulation (uphill contributing area), and Topographic Wetness Index (TWI) were derived (or taken directly) from the digital elevation model (DEM).

The occurrence of flowing artesian conditions requires the hydraulic head in the well to be above ground level. As described in Section 2, this condition can occur in both the topography-controlled and geologically-controlled conceptual models. In both cases, there needs to be a sufficiently high hydraulic head in the recharge area to overcome the head losses along the flow system, such that the head remains high enough to be above ground level where the well is drilled. Thus, the topography is an important consideration in both models.

Table 3: Factors considered for MCA.

Factor	Data File	Source
Elevation	BC Digital Elevation Model	GeoBC
Slope		
Curvature		
Flow Accumulation (uphill contributing area)		
Topographic Wetness Index		
Lineaments	Mapped from aerial orthophotos and satellite (LANDSAT TM) imagery	Natural Resources Canada
Soil Drainage	Soil Survey Spatial View/ BC Soil Survey Polygons	BC Data Catalogue /SIFT
Soil Texture		
Aquifer Type	Ground Water Aquifers	BC Data Catalogue
Stream Proximity	Freshwater Atlas Stream Network	BC Data Catalogue

Elevation

As a general observation, most flowing wells are located in low elevation areas, relative to the surrounding topography. Therefore, elevation (in the relative sense for an area) is a potential factor. Elevation has been used in previous studies related to flowing artesian conditions (e.g., Al-Abadi and Shahid, 2016), as well as spring occurrence (Ozdemir 2011; Bystron, 2018). Because elevation is potentially a factor in both unconsolidated and bedrock aquifers, it was examined for all three hydrogeological contexts. The elevation raster for the Okanagan bedrock is shown in Figure B1.

Slope

The slope, or difference in ground surface elevation from the recharge area to the well, is also an important consideration. Slope has two potential relationships with flowing artesian conditions. Firstly, flowing artesian conditions are frequently found in flat valley bottoms, where the slope is very low. Secondly, steeper slopes allow for higher hydraulic gradients, which may generate a strong driving force for groundwater flow. When there is low resistance to flow, for example along a permeable fracture, the head loss along the flow system may be minimal, thus resulting in higher heads further down the flow system. These seemingly contradictory situations (i.e., low slopes in valley lows vs high slopes), will depend on the specific hydrogeologic characteristics of flow system. Slope has been used in previous studies related to flowing artesian conditions (Al-Abadi and Shahid, 2016) and spring occurrence (Ozdemir, 2011; Bystron, 2018). Similar to elevation, slope is considered for all three hydrogeological contexts. The slope raster for the Okanagan bedrock is presented in Figure B2.

Curvature

Curvature is a measure of how a curved surface deviates from being a flat surface, i.e., the concavity or convexity of a surface. Curvature can potentially influence the occurrence of flowing artesian conditions because changes in curvature (both convexity vs concavity and the magnitude of these) influence the flow system. Concave surfaces (e.g., topographic depressions) will focus the flow, directing it inward, while convex surfaces (e.g., topographic mounds) will direct flow outward. Curvature is calculated from the DEM as the second derivative of elevation (I.e., the rate of change of the slope) using the curvature function in ArcMap. A flat surface is represented by a curvature value of zero, a negative value represents an upward convex surface, and a positive value represents a downward concave surface. The units of curvature are 1/100 of a metre and use the notation m^{-1}. Curvature has been used in previous studies related to flowing artesian conditions (Al-Abadi and Shahid, 2016) and spring occurrence (Ozdemir, 2011; Bystron, 2018). Curvature was evaluated for all hydrogeological contexts. The curvature raster for the Okanagan bedrock is presented in Figure B3.

Flow Accumulation (Uphill Contributing Area)

Flow accumulation is a topographically derived indicator of surficial drainage patterns and is based on the overland flow direction inferred from between the DEM raster cells. Flow accumulation represents the upslope area that would contribute overland flow to a point (i.e., raster cell). The raster cell values of flow accumulation indicate the number of cells upslope where water would flow into that cell. Thus, flow accumulation represents the uphill (topography derived) contributing area to a well. Cells with higher values therefore represent locations with larger contribution areas. Groundwater flow frequently mimics topography, and therefore, using this surface flow accumulation tool is assumed to represent subsurface (i.e., groundwater) flow, at least in areas of sufficient relief. Flowing artesian conditions are therefore potentially 'more likely than not' to occur where the subsurface flow contribution area is large. The term flow accumulation is used throughout the rest of this report.

Topographic Wetness Index

Topographic Wetness Index (TWI) is a steady state wetness index that uses the calculated slope and flow accumulation (Equation 1; Mattivi et al., 2019). The index is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. Higher TWI values indicate that an area is more likely to accumulate water due to a larger contribution area and lower slope.

$$TWI = \ln\left(\frac{SCA}{tan\varphi}\right) \quad \text{(Eq. 1)}$$

where, SCA is the specific contribution area; the local upslope area draining through a certain point per unit contour length, and φ is the slope angle.

TWI is considered as a factor for flowing well occurrence because high soil moisture values may be associated with upward gradients in topographically controlled flowing artesian conditions (Figure 3). TWI is used as a hydrological indictor for soil wetness; however, the equation is primarily a terrain descriptor as is it derived from a DEM and therefore can be applied to all three hydrogeologic contexts.

4.2.2 Lineaments

Lineaments are surficial expressions of faults and fractures and thus are often associated with fracture networks. Faults and fractures can act as conduits for groundwater flow over large distances. In less permeable bedrock they can be the primary factor that controls groundwater flow. Fuller (1908) presented a schematic where the flowing artesian conditions were presented in a fractured bedrock aquifer. He showed a daylighting fracture upslope that allowed for recharge to enter the aquifer and the bedrock to act as a confining unit, which preserved the hydraulic head creating flowing artesian conditions downslope.

Lineament density was examined as a potential factor influencing the occurrence of flowing bedrock wells. Lineament density was only considered for the Okanagan bedrock hydrogeological context because lineaments most commonly occur in bedrock. Previous work by Voeckler and Allen (2012) used mapped lineaments in the Okanagan Basin to estimate the regional scale hydraulic conductivity of the fractured bedrock based on lineament density. The regional scale lineament data, provided by Natural Resources Canada, were mapped using both detailed aerial orthophotos and satellite (LANDSAT TM) images from the near-infrared band 4 (Figure 11). The extent of the lineament data in the Okanagan Basin is limited due to limited visibility in highly treed areas and areas with sediment cover. As such, because the main valley bottom tends to have a thicker layer of surficial sediment, lineaments are generally not mapped throughout the valley bottom.

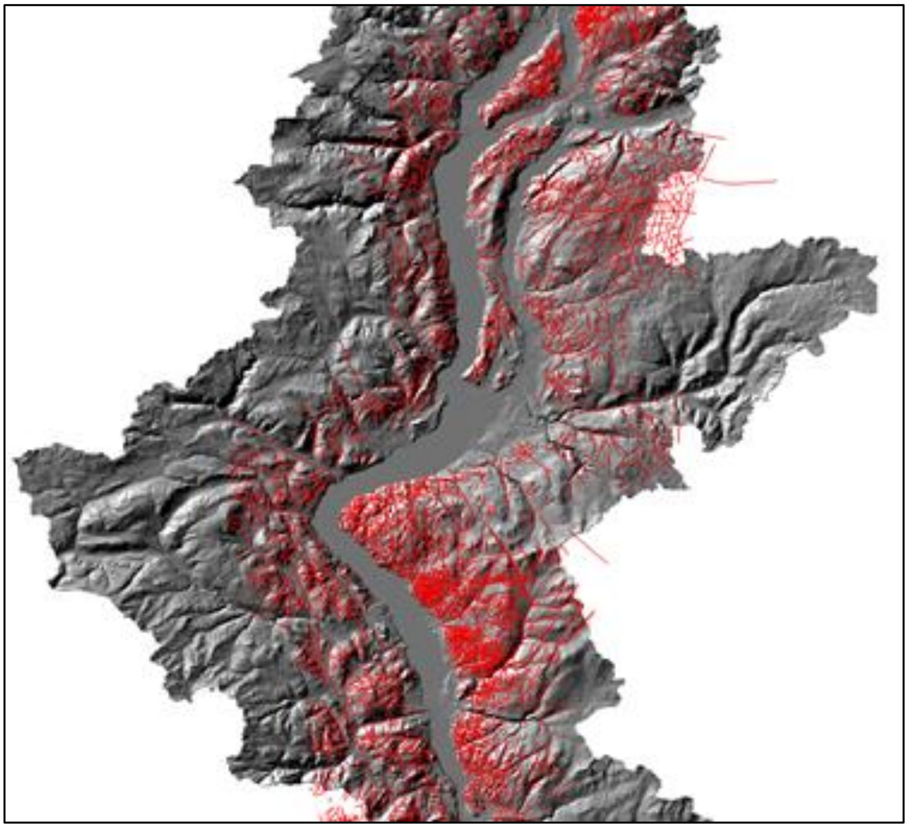

Figure 11: Mapped lineaments in the Okanagan Basin. Source: Natural Resources Canada.

Voeckler and Allen (2012) associated the lineaments with three sub-vertical fracture sets that they had mapped in outcrop. The sub-horizontal fracture set mapped in outcrop could not be associated with the lineaments, because lineaments that daylight on the surface tend to have a bias towards steeply dipping fractures and faults. In this study, the lineament data were categorised into these three fracture sets based on the lineament strike direction (see Figure B8). Sets 1 and 2 have similar strike ranges and are distinguished based on the dip direction measured in outcrop (Voeckler and Allen, 2012).

In this study, kernel density maps of the lineaments were produced (see Appendix A), following a similar approach by Voeckler and Allen (2012). Kernel density is a spatial representation of density. It is a magnitude-per-unit density measure and represents the density of polyline features (i.e., lineaments).

4.2.3 Soil

Two soil related factors were considered for the MCA: soil drainage and soil texture. Soil has the capacity to act as a confining layer to an aquifer if the soil hydraulic conductivity (K) is significantly lower than the aquifer K and the soil is sufficiently thick. The low K increases the resistance to flow through the soil, resulting in a steep hydraulic gradient across the soil, and possibly a potentiometric surface in the underlying aquifer that is above ground surface where there is an upward vertical gradient. Accordingly, the system can mimic the conditions in the geologically-controlled model, resulting in flowing artesian conditions. Both drainage and texture were evaluated for each hydrogeological context.

4.2.4 Presence of Confining Unit

Flowing well occurrence was examined with respect to the presence of confining units of mapped aquifers. In the geologically-controlled model for flowing artesian conditions, the presence of a confining unit is a requisite for creating sufficient resistance to flow to result in a potentiometric surface above ground surface. Therefore, the presence of a confining unit is an important factor for determining the occurrence of flowing artesian conditions.

Well logs can be used to determine where a confining unit is present; however, due to the large number of wells in both study areas, this approach was not feasible (e.g., the Fraser Valley has ~16000 well logs many of which have not been correlated to a specific mapped aquifer). In lieu of using well logs at this regional scale, the extent of the confined aquifer polygons was used to determine the presence of a confining unit. Well logs were examined in select case study areas to support the MCA results (see Section 6).

The presence of a confining unit was not considered in the Okanagan bedrock context because of the 125 flowing bedrock wells in the Okanagan, only a small percentage were overlain by unconsolidated aquifers (11 by confined aquifers and 14 by unconfined aquifers). Therefore, this factor was only considered for the Fraser Valley unconsolidated and Okanagan unconsolidated hydrogeological contexts.

4.2.5 Stream Proximity

Flowing well occurrence was examined with respect to stream proximity. Streams can be classified as losing or gaining, depending on whether the stream contributes water to the aquifer (losing) or the aquifer contributes water to the stream (gaining). For a gaining stream, the hydraulic gradient in the aquifer is typically upwards beneath the stream, which allows for groundwater to discharge into the stream. The upward hydraulic gradient defines the discharge zone. Therefore, gaining streams can have hydrogeologic conditions that mimic the topography-controlled models for flowing artesian conditions (Figure 3). By association, flowing artesian conditions may be ‘more likely than not’ to occur closer to gaining streams. It is important to note, however, that streams can transition naturally from gaining to losing depending on the season (due to fluctuations in groundwater levels), the topography and hydrogeologic conditions. In this study, an assumption is made that all streams are gaining, and stream proximity was considered as a factor.

4.3 Wilcoxon Rank Sum Test and Qualitative Analysis

The Wilcoxon Rank Sum Test (Wilcoxon Test) was used to determine which factors are statistically significant from the perspective of “predicting” whether flowing artesian conditions will likely occur or not. The Wilcoxon Test is appropriate for determining statistical significance because it is valid for non-parametric data (i.e., data that do not follow a normal or Gaussian distribution).

The Wilcoxon Test compares two data sets (here, flowing and non-flowing wells) to determine if they come from the same population. The idea is that if they are determined to come from the same population for the factor being tested (e.g., slope), there is statistically no difference between the flowing wells and the non-flowing wells with regard to that factor. The Wilcoxon Test compares the median values of the two data sets.

Statistical tests are posed as hypotheses:

> *Null Hypothesis:* The two data sets are from the same population.
>
> *Example Null Hypothesis:* The elevations at flowing and non-flowing wells are from the same population.

Each data set contains the values for each factor occurring at the flowing or non-flowing wells. Categorical data were assigned a numerical value to conduct the Wilcoxon Test. For this study a rejection of the null hypothesis at a significance level of 15% was required for a factor to be considered statistically significant and ultimately carried over for the MCA.

To supplement the Wilcoxon Test for each factor, a qualitative comparison was conducted by comparing the histograms of the percent frequencies of each factor. For example, the slope factor for the Okanagan bedrock context is presented in Figure 12. Non-flowing wells occur more frequently in areas with lower slope. Slopes that are <12° have non-flowing wells occurring more frequently than flowing wells, and slopes that are >12° have flowing wells occurring more frequently than non-flowing wells, with the exception of slopes >28° where only a small portion of flowing and non-flowing wells occur. The Wilcoxon Test determined that the difference in the flowing and non-flowing wells is significant at the 15% level, meaning the wells are from two different populations. However, there is still overlap in the slope ranges for flowing and non-flowing wells; therefore, the distribution alone in Figure 12 does not allow for conclusions to be drawn about where flowing wells can and cannot occur relative to non-flowing wells. This was a common observation among the qualitative examination of factors. The histograms for each factor are shown in Appendix C.

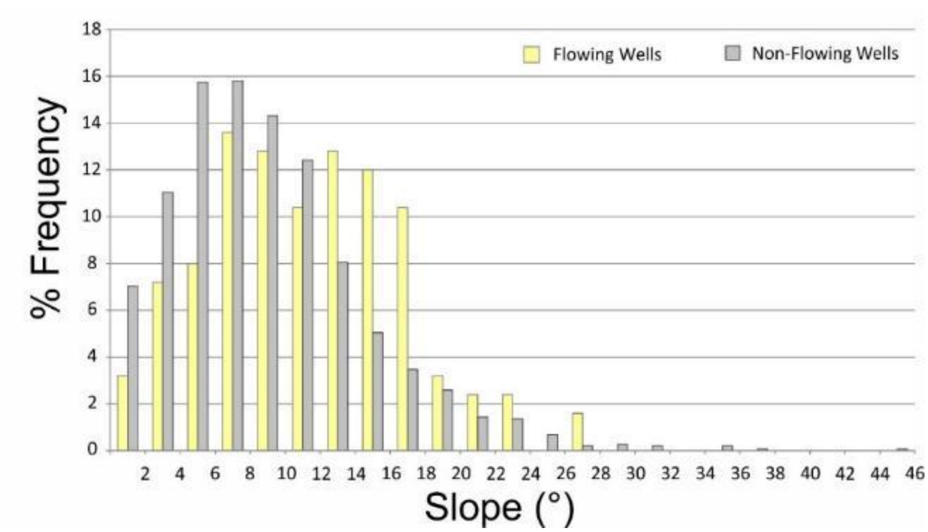

Figure 12: Percent frequency of the occurrence of flowing and non-flowing wells for the slope factor in the Okanagan bedrock context.

4.4 Final Factors Used for Each MCA

Appendix A describes the results of the Wilcoxon tests used to determine the significance of each factor. A summary of the final factors used (>15% Wilcoxon significance level) for MCA in each hydrogeological context is provided in Table 4. Factors that were determined to be significant are indicated with 'Y', factors that were deemed insignificant are indicated with 'N', and factors that were not relevant are indicated with 'n/a' (e.g., lineaments in unconsolidated). Tables A4 – A6 show the detailed results.

Table 4: Factors examined for the Multi-Criteria Analysis (MCA) in each of the three hydrogeological contexts. Factors that were determined to be significant are indicated with 'Y', factors that were deemed insignificant are indicated with 'N', and factors that were not relevant are indicated with 'n/a'.

Factor	Okanagan: Bedrock	Okanagan: Unconsolidated	Fraser Valley: Unconsolidated
Elevation (at 2 grid resolutions[1])	Y	Y	Y
Slope (at 2 grid resolutions[1])	Y	Y	Y
Curvature (at 2 grid resolutions[1])	Y	N	N
Flow Accumulation	Y	Y	Y
Topographic Wetness Index	N	Y	Y
Lineaments (combined and sets)	Y	n/a	n/a
Soil Drainage	N	Y	Y
Soil Texture	N	N	N
Presence of Confining Unit	N*	Y	Y
Stream Proximity	N	Y	Y

[1] Elevation, slope and curvature were assessed at two grid resolutions (see Section A1 in Appendix A)
* No analysis was done for the 'Presence of Confining Unit' factor in the Okanagan bedrock context due to the limited overlap of bedrock and non-bedrock aquifers, but the factor is considered relevant.

Elevation and slope were used for each hydrogeological context. Both were used in the MCA at the original DEM cell size (20.5 m x 20.5 m). Curvature was only significant in the bedrock context due to the steep topography. Curvature was calculated using a larger DEM cell size (41 m x 41 m) because it gave more reasonable values (curvature ranging from approximately -8 to +8) at the larger cell size (see Section A1 in Appendix A). Flow accumulation was significant for all contexts, while topographic wetness index was only significant for the two unconsolidated contexts.

The lineaments factor was analyzed as lineament sets rather than the combined dataset due to differences in spatial distributions and the different ranges in kernel densities between the lineament sets (see Section 4.2.2). This resulted in differences in the Wilcoxon Tests for each lineament set (see Section A2 Appendix A).

Soil drainage was only significant in the two unconsolidated contexts. Soil drainage was used in preference to soil texture in the final MCAs, not only because drainage showed a stronger significance but also because soil texture affects the drainage capacity of soil, and so texture is redundant. Presence of confining unit was significant for both unconsolidated contexts. This factor is considered important for the bedrock context; however, there was insufficient information to assess this factor in a bedrock context. Finally, stream proximity was only significant in the unconsolidated contexts.

4.5 Determination of Relative Importance of Factors and Their Weights

Once the statistically significant factors were identified (Table 4), the next step in the MCA was to assign weights to each of them. Factor weights were determined through a modification of Saaty's (1987) Analytical Hierarchy Process (AHP), which is a pairwise comparison method. The method is used to rank factors against each other to determine which factors are more important / have the greatest influence. Saaty's (1987) AHP is a commonly used, qualitative method for MCAs.

In Saaty's method, each factor is compared with every other factor (pairwise comparison) and then ranked in a qualitative fashion according to its relative importance to other factors. In this study, Wilcoxon Test was used to test pairs of factors to determine the relative importance[3] of each factor (see Section A6 in Appendix A). This is a novel approach that was taken to add a quantitative aspect to

[3] Relative importance is the same as Saaty's Intensity of importance on an absolute scale.

Saaty's original methodology. The Wilcoxon Tests used to determine the relative importance of the factors were performed using the entire dataset (all flowing and non-flowing wells in each hydrogeological context). The relative importance in each pairwise comparison was determined by comparing the significance level of each factor.

Table 5 shows the final weights for each factor. The ranges of Wilcoxon significance levels vary for each. The Okanagan bedrock (Table A4) has the highest diversity in the Wilcoxon significance levels (i.e., green cells across a range of significance levels), which results in more variation for the factor weights (Table 5). The Okanagan and Fraser Valley unconsolidated have more factors of equal importance. For example, in the Fraser Valley unconsolidated context (Table A6), there is a more homogenous distribution of weights as all but one factor (flow accumulation) has a Wilcoxon significance level of 0.001%. The Okanagan unconsolidated (Table A5) has only two factors that did not contribute equally to the occurrence of flowing wells (flow accumulation and stream proximity).

Table 5: Weights (rounded) determined for factor through the modified Analytical Hierarchy Process for the Okanagan bedrock, Okanagan unconsolidated and Fraser Valley.

Okanagan Bedrock	Weights
Elevation	0.04
Slope	0.30
Curvature	0.02
Flow Accumulation	0.30
Lin. Density 1	0.14
Lin. Density 2	0.07
Lin. Density 3	0.14

Okanagan Unconsolidated	Weights
Elevation	0.18
Slope	0.18
TWI	0.18
Flow Accumulation	0.07
Stream Proximity	0.02
Soil Drainage	0.18
Confining Unit	0.18

Fraser Valley	Weights
Elevation	0.16
Slope	0.16
TWI	0.16
Flow Accumulation	0.02
Stream Proximity	0.16
Soil Drainage	0.16
Confining Unit	0.16

4.6 Factor Standardization

All factors must be standardized to the same scale before the MCA weighted linear equation can be applied. Standardization for each factor is unique to each of the three hydrogeological contexts and converts each factor's original scale (e.g., masl for elevation) to a dimensionless scale of 0 – 100.

The bin intervals and standardized scores were determined from a subset of wells in each hydrogeological context. Twenty-five percent (25%) of the flowing wells were randomly selected and reserved for validation (validation wells) in order to evaluate the MCA likelihood maps (see Section 4.10). The remaining 75% of the data were used for the analysis (analysis wells).

Table 6 displays the number of flowing wells used as analysis or validation wells. Only the analysis wells were used to determine the bin intervals and standardized scores. The factor standardization approach is described in Section A7 in Appendix A.

Table 6: The distribution of flowing wells that were reserved for analysis and for validating the final MCA maps. Of all flowing wells in each area, 25% were reserved for validation and 75% were used for analysis.

	Total # of Flowing Wells	Analysis Wells	Validation Wells
Okanagan Bedrock	125	94	31
Okanagan Unconsolidated	408	306	102
Fraser Valley Unconsolidated	785	589	196

4.7 Weighted Linear Equations

Equation 2 (also shown in Figure 10) was used to develop three weighted linear equations (Equations 3 to 5), one for each hydrogeological context. The equations were applied to every cell in the raster.

$$MCA\ Standardized\ Likelihood\ Score = [f_1 * (w_1)] + [f_2 * (w_2)] + \cdots [f_n * (w_n)] \quad \text{(Eq. 2)}$$

where:

f_n is the standardised score of a factor

w_n is the weight determined for f_n.

Okanagan Bedrock

$$MCA\ Standardized\ Likelihood\ Score = [DEM * (0.04)] + [Slope * (0.30)] + [Curvature * (0.02)] + [Flow\ Accumulation * (0.30)] + [Lineament\ Density\ Set\ 1 * (0.14)] + [Lineament\ Density\ Set\ 2 * (0.07)] + [Lineament\ Density\ Set\ 3 * (0.14)] \quad \text{(Eq. 3)}$$

Okanagan Unconsolidated

$$MCA\ Standardized\ Likelihood\ Score = [DEM * (0.18)] + [\ Slope * (0.18)] + [Flow\ Accumulation * (0.07)] + [TWI * (0.18)] + [Stream\ Proximity * (0.14)] + [Soil\ Drainage * (0.18)] + [Confining\ Unit * (0.18)] \quad \text{(Eq. 4)}$$

Fraser Valley Unconsolidated

$$MCA\ Standardized\ Likelihood\ Score = [DEM * (0.16)] + [\ Slope * (0.16)] + [Flow\ Accumulation * (0.02)] + [TWI * (0.16)] + [Stream\ Proximity * (0.16)] + [Soil\ Drainage * (0.16)] + [Confining\ Unit * (0.16)] \quad \text{(Eq. 5)}$$

4.8 Map Classification and Percent Frequency Distributions

The standardized MCA scores were classified by the relative likelihood of occurrence, that is, where flowing wells are ‘more likely than not’ to occur than non-flowing wells. To relate the standardized MCA scores to likelihood of occurrence, the percent frequency distributions of flowing and non-flowing wells were examined. The Standardized MCA Score is a dimensionless scale resulting from the weighted linear combination (Equations 3-5). A score of 100 represents a cell where the value for every factor occurred with the highest percent frequency. Lower scores therefore represent areas where the factors had low occurrences of flowing wells.

Figure 13 shows the percent frequency distributions of the flowing and non-flowing wells together. These distributions were used to determine the scores at which flowing wells become ‘more likely than not’ to occur than non-flowing wells. Areas on the maps determined as being ‘more likely than not’ were identified when the percent frequency of flowing wells exceeded the percent frequency of non-flowing wells. Two different methods for classification were used, one method for the Okanagan bedrock and another for the Okanagan and Fraser Valley unconsolidated contexts. Different methods were used because of the differences in the distributions between the flowing vs non-flowing wells (Figure 13).

The first classification method was applied to the Okanagan and Fraser Valley unconsolidated contexts. The two unconsolidated hydrogeologic contexts have flowing wells with distributions skewed right (higher MCA scores) and non-flowing wells with distributions skewed left (lower MCA scores) (Figure 13). In both unconsolidated contexts, flowing wells have greater percent frequencies than non-flowing wells at standardized MCA scores > 70. Therefore, scores > 70 (illustrated by the red arrows and dashed lines on Figure 13) are determined to be areas where flowing wells are ‘more likely than not’ to occur. This marks the upper threshold for ‘more likely than not’ for the Okanagan and Fraser Valley unconsolidated contexts.

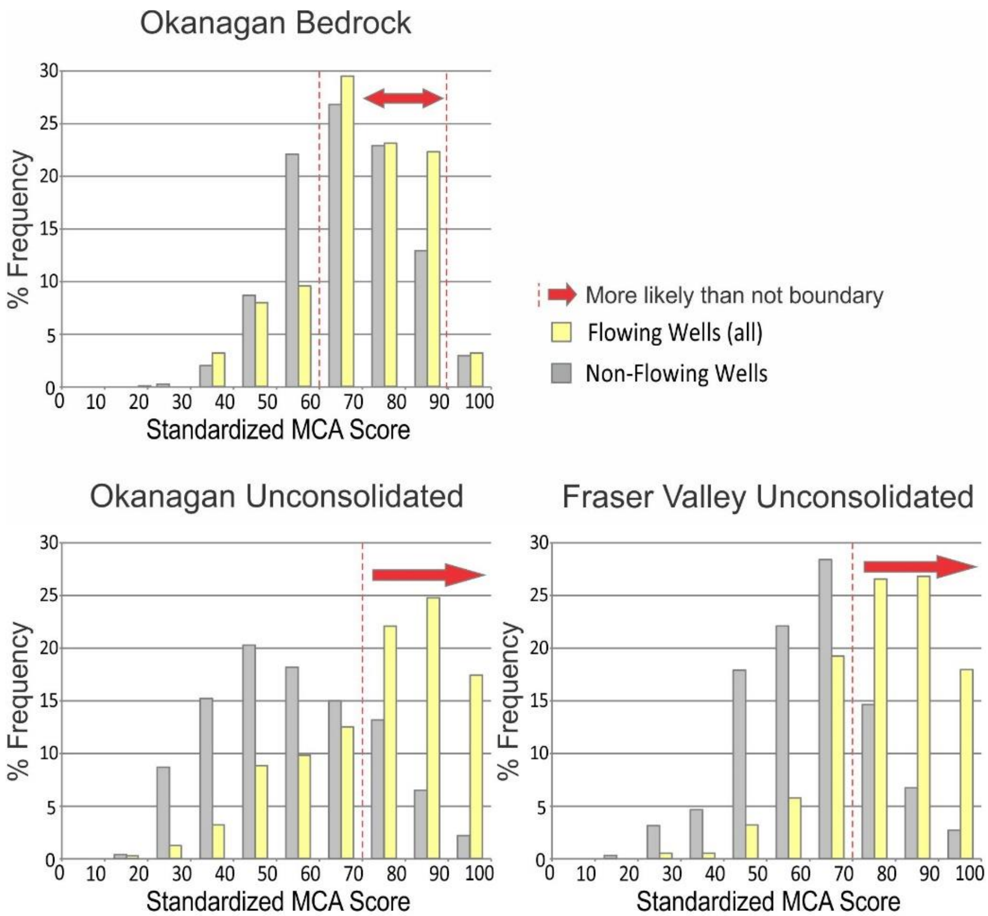

Figure 13: Percent frequency distributions of all flowing wells (validation and analysis combined) and non-flowing wells for each hydrogeologic context. Johnson (2021) shows similar graphs with validation and analysis wells separated. The validation wells have a similar distribution to the analysis wells.

For the bedrock context, classification proved more challenging because the distributions between flowing and non-flowing wells was not as distinct as the unconsolidated contexts. The flowing wells have greater percent frequencies at standardized MCA scores > 60 (Figure 13). However, there is only a small difference in the frequencies in the 70-80 interval, while intervals 60-70 and 80-90 have noticeably higher frequencies for non-flowing wells. Therefore, we experimented with the classification. If all intervals with scores > 60 are classified as 'more likely than not" the MCA map appears almost entirely red. Equally, if only the 80-90 interval is classified as 'more likely than not', then 60-70 interval is excluded. To remain consistent with the unconsolidated context, the lower cut-off for 'more likely than not' was the bin where there are more flowing wells than non-flowing wells (> 60). Therefore, the binned intervals 60-70, 70-80, and 80-90 were each assigned a different shade of red to indicate where flowing wells are 'more likely than not' to occur. Scores > 90 were excluded as there are only a few (< 5% of wells) in this range. This classification approach is therefore precautionary.

In addition to differences in distributions for each hydrogeological context, there are several other noteworthy differences. In the Okanagan bedrock context, the greatest difference between the percent frequencies of flowing vs non-flowing wells is ~5%, whereas the Okanagan unconsolidated and the Fraser Valley unconsolidated contexts have differences of at least ~5% and maximum differences of ~15% (Figure 13). Additionally, in the Okanagan bedrock the bin values of more moderate scores (60 –

90) have the highest percent frequencies of flowing wells, whereas the Okanagan and Fraser Valley unconsolidated contexts have the highest percent frequency of flowing wells in bins with scores > 70. In each hydrogeologic context the bin intervals with the highest percent frequency for non-flowing wells are lower than the bin intervals with the highest percent frequency for flowing wells of the same context. No flowing wells occur in the lowest scoring bin interval for each hydrogeologic context.

4.9 Standardized MCA Score Statistics

The score statistics for flowing wells (only cells with flowing wells) were compared with the score statistics for the entire map (all cells in the map) (Table 7). Each hydrogeologic context had mean flowing well scores that are higher than the mean map scores, indicating a preliminary conclusion that the maps are able to identify where flowing artesian conditions are 'more likely than not'. This conclusion is drawn based on the fact that flowing wells occupy a small spatial proportion of each map, and thus the likelihood of these areas should be higher than the average likelihood. Additionally, the flowing well scores all have minimum scores >15 points higher than the minimum map scores, indicating that the MCA maps are scoring flowing wells as 'more likely than not'.

Table 7: Statistics for the standardized MCA scores for the cells in the MCA map rasters (Map Score) and the statistics for flowing well Standardized MCA scores. The flowing well score represents the entire dataset (including the analysis and validation wells)

	Okanagan Bedrock		**Okanagan Unconsolidated**		**Fraser Valley Unconsolidated**	
	Map Score	Flowing Well Score	Map Score	Flowing Well Score	Map Score	Flowing Well Score
Maximum	101*	93.15	99.00	99.00	98.00	98.00
Minimum	0.47	35.15	4.98	19.90	1.78	20.46
Mean	56.94	69.61	33.26	72.79	60.54	76.75
Standard Deviation	14.59	13.69	11.75	17.45	17.49	13.30

* The Okanagan bedrock context has a Maximum Score > 100 due to rounding in the weight calculations.

4.10 Map Validation

The final step identified for the MCA workflow (see Figure 10) is to validate the maps produced. The map validation process has two main objectives:

1. To determine if the maps accurately predict where flowing wells will occur.
2. To determine that the maps are specifically identifying the locations of flowing wells, and not both flowing and non-flowing wells.

The Wilcoxon Test was used to validate the maps and assess both objectives. This was done by running three tests on the results from each MCA. Each test was conducted at a 5%, 10% and 15% significance level. In order for a significance level to be considered the 'highest achieved significance level' for a hydrogeologic context, all tests must fulfill the desired outcome. Desired outcomes are described below.

Objective 1

To address the first objective, a single Wilcoxon Test was performed to compare the analysis wells to the validation wells.

The hypothesis posed for the first objective is:

Null Hypothesis: The analysis wells and the validation wells are from the same population.

For this test, a 'failure to reject the null hypothesis' result is the desired outcome.

Objective 2

The second objective is assessed by performing two Wilcoxon Tests. The first test compares the validation wells to the non-flowing wells. The second Wilcoxon Test is performed on the entire flowing well dataset and the non-flowing wells. Both of these tests are meant to compare the flowing vs the non-flowing wells.

The hypothesis posed for the first test of the second objective is:

> *Null Hypothesis*: The validation wells and the non-flowing wells are from the same population.

The hypothesis posed for the second test of the second objective is:

> *Null Hypothesis*: The flowing wells and the non-flowing wells are from the same population.

For these tests the desired outcome is a 'rejection of the null hypothesis' result.

Wilcoxon Results

The Wilcoxon Test results are displayed in Table 8. Each hydrogeologic context met the desired outcome at an acceptable significance level. Across both objectives and tests, the Okanagan bedrock context achieved significance levels of 5%-15%, while the Okanagan unconsolidated and Fraser Valley unconsolidated contexts both achieved 5% significance levels. The significance level for Okanagan bedrock was limited by the Wilcoxon Test comparing the validation and non-flowing wells (Objective 2 – Test 1 at 15%) as the other two tests passed at a significance level of 5%. This is likely because of the small sized validation well data set used for Objective 2 – Test 1. The Wilcoxon Test results indicate that each MCA map met the goals they were meant to achieve with varying, but high success.

Table 8: Wilcoxon Test results for each hydrogeologic context for each objective and test with the highest achieved significance level indicated.

	Significance Level	**Objective 1**	**Objective 2**	
		Analysis vs Validation Wells (Test 1)	Validation vs Non-flowing Wells (Test 1)	All Flowing vs Non-Flowing Wells (Test 2)
Okanagan Bedrock	5% - 15%*	Fail to reject Null Hypothesis	Reject Null Hypothesis	Reject Null Hypothesis
Okanagan Unconsolidated	5%	Fail to reject Null Hypothesis	Reject Null Hypothesis	Reject Null Hypothesis
Fraser Valley Unconsolidated	5%	Fail to reject Null Hypothesis	Reject Null Hypothesis	Reject Null Hypothesis

* Objective 1 – Test 1 and Objective 2 – Test 2 passed the Wilcoxon Test at a 5% significance level, while Objective 2 – Test 1 passed the Wilcoxon Test at a 15% significance level.

5. LIKELIHOOD MAPS FOR FLOWING ARTESIAN CONDITIONS

The maps produced by the MCA are described in different subsections for each hydrogeological context. Each map is presented in two formats: without displaying the reported flowing wells and displaying the flowing wells, to enable better visualization of the results. The Okanagan bedrock context displays the non-flowing wells with the flowing wells; the non-flowing wells are omitted from the other two contexts because the high well density of non-flowing wells obscures the scores. Red cells identify areas in the maps where flowing wells are 'more likely than not' to occur and blue cells indicate areas where non-flowing wells are 'more likely than not' to occur. Chapter 5 takes a closer look at the map results for specific regions in each hydrogeologic context.

5.1 Okanagan Bedrock

The MCA map for the Okanagan bedrock context (Figure 14 and Figure 15) shows areas classified as 'more likely than not' (red cells) occurring in a band down the center of the valley on both sides of Okanagan Lake. Importantly the lineament datasets are limited in their extent, which consequently limits the possible standardized MCA scores outside of that extent. Lineament density for all three lineament sets combined contributes 35% (i.e., a standardized MCA score of 35) in the weighted linear equation (Equation 3). Therefore, any cells falling outside the extent of lineament density map will only be able to achieve a maximum MCA score of 75. If the lineament dataset was expanded to include the periphery areas, then there could be additional areas mapped as 'more likely than not'. Nevertheless, the absence of lineament data at high elevations is likely not of practical concern as few wells are drilled at high elevation (Figure 15).

Existing flowing bedrock wells are distributed across the basin in small, dispersed clusters. These small clusters of flowing wells always tend to occur with clusters of non-flowing wells. In fact, there are only a few areas where non-flowing bedrock wells occur without flowing wells also occurring. The flowing well locations are predominantly associated with areas mapped as 'more likely than not' (Figure 15); however, these areas do not appear as clusters around the flowing bedrock wells. Rather these areas are widespread throughout the valley. There are two main reasons for this.

1. At a small scale, red cells juxtapose blue cells throughout the mapped area. This leads to a map that has a very 'grainy' appearance with adjacent cells having higher and lower likelihood. One potential reason for the graininess of the map is the high weight assigned to flow accumulation (0.30 in Equation 3). Flow accumulation varies significantly between adjacent cells, and so the raster map appears grainy at small scales (see Figure B4). Curvature also results in significant differences between adjacent cells (see Figure B3); although, curvature was assigned a relatively low weight (0.02 in Equation 3) and so does not impact the final map noticeably.
2. Standardized scores are more moderate (see Figure 13) in the Okanagan bedrock context rather than having a few binned intervals with high standardized scores and the majority with low standardized scores (i.e., as in the unconsolidated contexts). This results in the more dispersed appearance of areas mapped as 'more likely than not'.

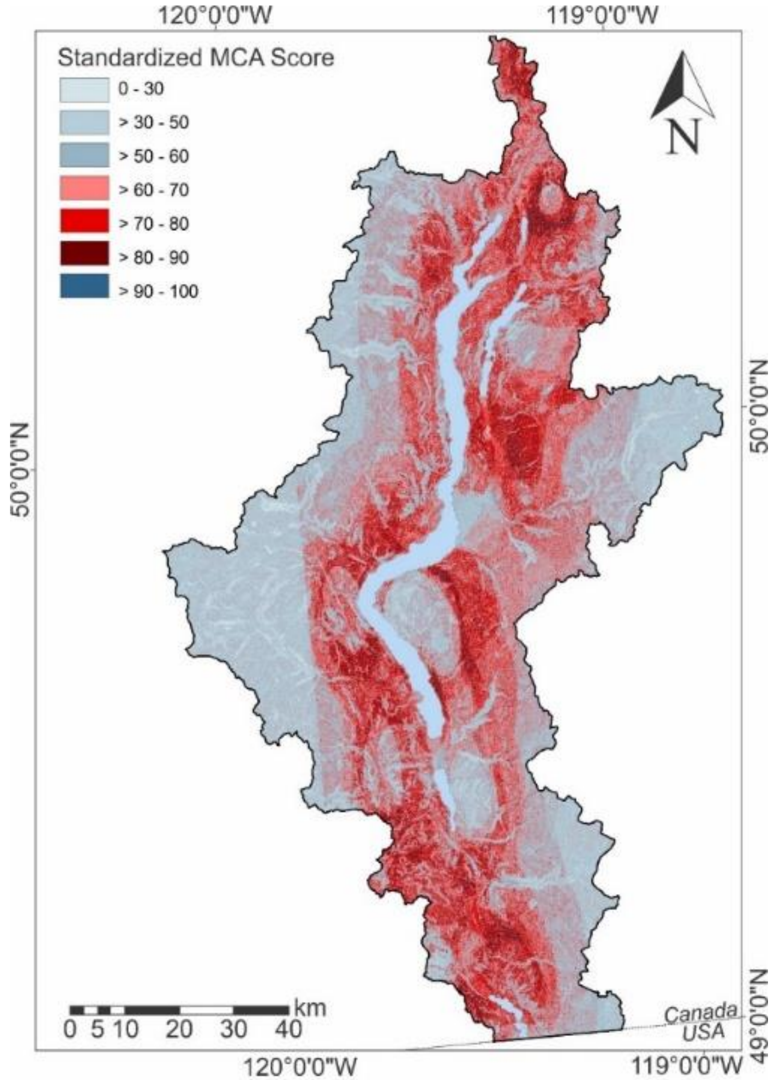

Figure 14: Okanagan bedrock MCA map. Red cells indicate where flowing wells are 'more likely than not' to occur and blue cells indicate where non-flowing wells are more likely to occur.

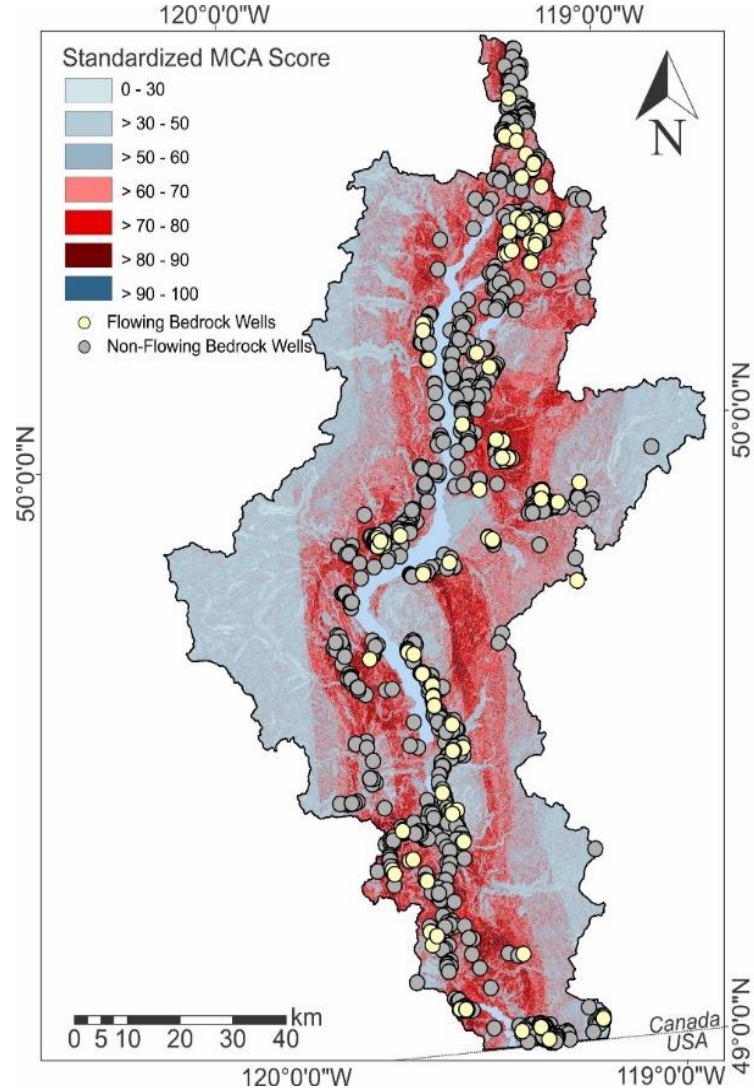

Figure 15: Okanagan bedrock MCA map showing the locations of flowing bedrock wells. Red cells indicate where flowing wells are 'more likely than not' to occur and blue cells indicate where non-flowing wells are more likely to occur.

While flowing wells have similar spatial distributions to non-flowing wells, they have somewhat different depth distributions. The depth statistics for the Okanagan bedrock context are displayed in Table 9. The flowing wells occur at slightly shallower median depths (85 metres below ground surface (mbgs) vs. 91 mbgs) and have a lower standard deviation. Flowing wells are specifically occurring more than non-flowing wells at depths ranging 60 – 80 mbgs (Figure 16). One potential reason that flowing wells occur at shallow depths is because once drillers encounter flowing artesian conditions, they typically do not continue drilling. This indicates that consideration for encountering flowing conditions should always be given when drilling into bedrock in the regions mapped as 'more likely than not' regardless of well depth, and that flowing artesian conditions are possible in all bedrock aquifers through much of the Okanagan.

Table 9: Okanagan bedrock context depth statistics for flowing and non-flowing wells.

	Flowing Wells	Non-Flowing Wells
Count	125	1468
Minimum Depth (mbgs)*	6	3
Maximum Depth (mbgs)	305	317
Mean Depth (mbgs)	90	100
Median Depth (mbgs)	85	91
Geomean Depth (mbgs)	79	85
Standard Deviation (m)	44	51

* Wells with a depth of 0 were excluded from the results (1 flowing, 5 non-flowing)

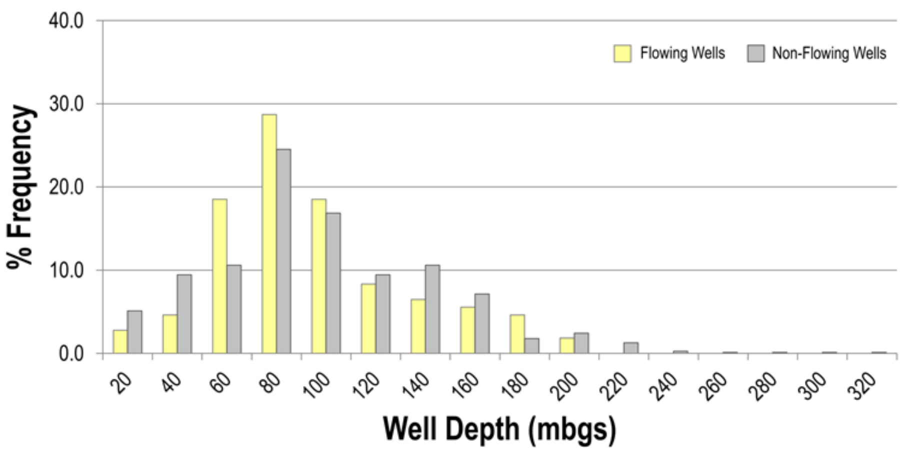

Figure 16: Percent frequency distribution of flowing and non-flowing well depths in the Okanagan bedrock context. Units in metres below ground surface.

5.2 Okanagan Unconsolidated

The MCA map for the Okanagan unconsolidated context (Figure 17 and Figure 18) shows several isolated areas mapped as 'more likely than not', primarily within the valley bottom. But, smaller areas for flowing artesian conditions are 'more likely than not' also occur in the major (regional scale) tributary valleys that represent incised areas and therefore topographic lows (e.g., east of Kelowna). The MCA analysis for the Okanagan unconsolidated context was applied to the entire Okanagan Basin; however, the higher elevations in the mountainous areas typically do not have sufficiently thick surficial materials to form extensive aquifers.

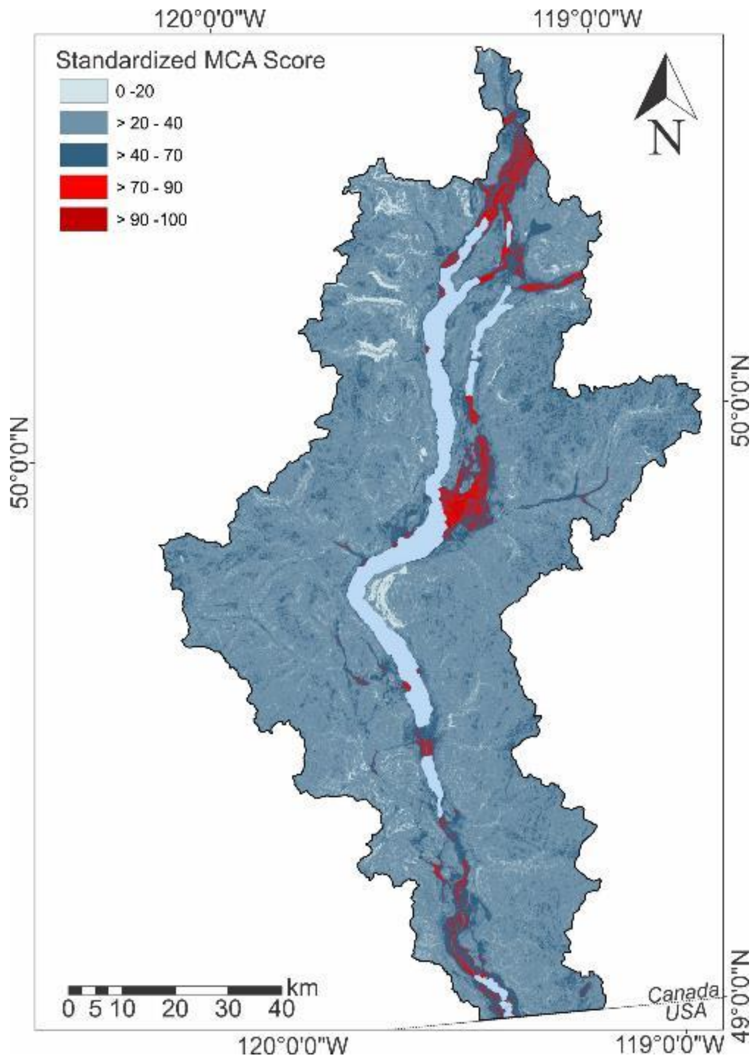

Figure 17: Okanagan unconsolidated MCA map. Red cells indicate where flowing wells are 'more likely than not' to occur and blue cells indicate where non-flowing wells are more likely to occur.

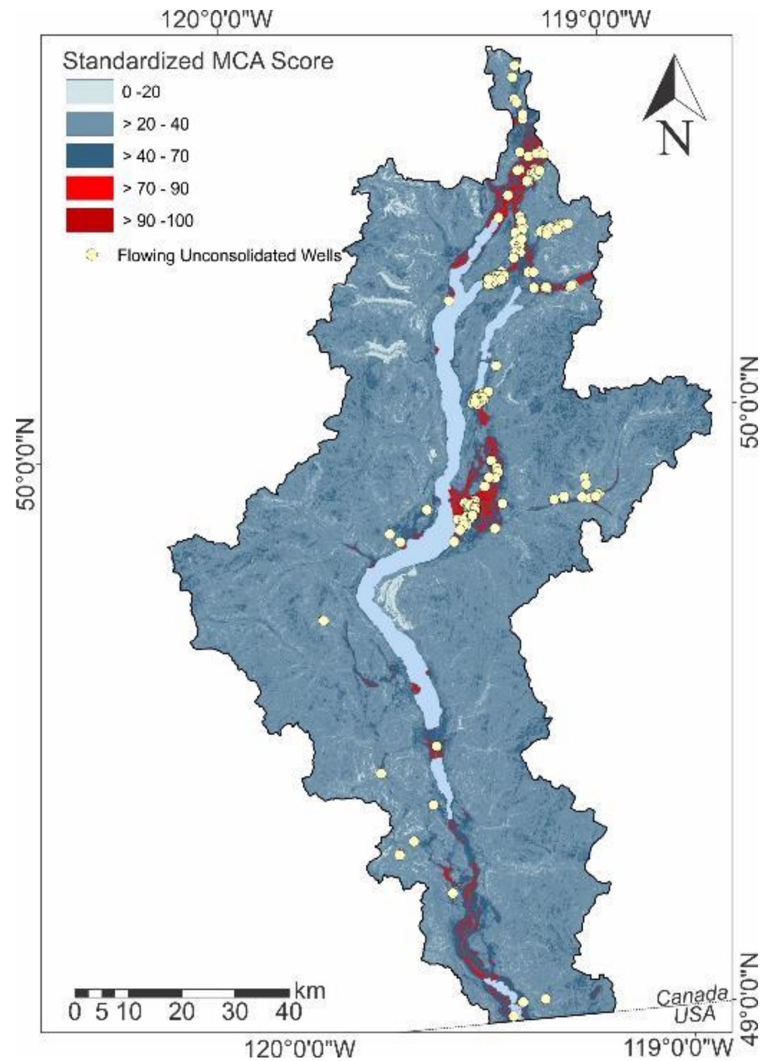

Figure 18: Okanagan unconsolidated MCA maps showing the locations of flowing wells in unconsolidated materials. Red cells indicate where flowing wells are 'more likely than not' to occur and blue cells indicate where non-flowing wells are more likely to occur.

The majority of the flowing wells cluster within the 'more likely than not' areas (Figure 18). For example, Vernon Creek and Coldstream all have provincial well drilling advisories for flowing artesian conditions. Based on the mapping results, the area around Armstrong also has a number of flowing wells located in areas mapped as 'more likely than not' which could be considered for a well drilling advisory. Well drilling advisories for flowing artesian conditions are given further consideration in Section 5.

All of the large clusters of flowing wells occur in areas with a mapped confined aquifer; this relationship can be seen by comparing Figure 18 to Figure 19. The majority of the confined aquifers have flowing wells within their polygon boundaries (Figure 19) with a few exceptions for smaller aquifers in the region. A few sporadic wells do not occur within the mapped extent of confined aquifers. Overall, the mapping results suggest that flowing wells in unconsolidated materials can be largely attributed to the geologically-controlled model, i.e., the presence of a confining unit may be a determining factor.

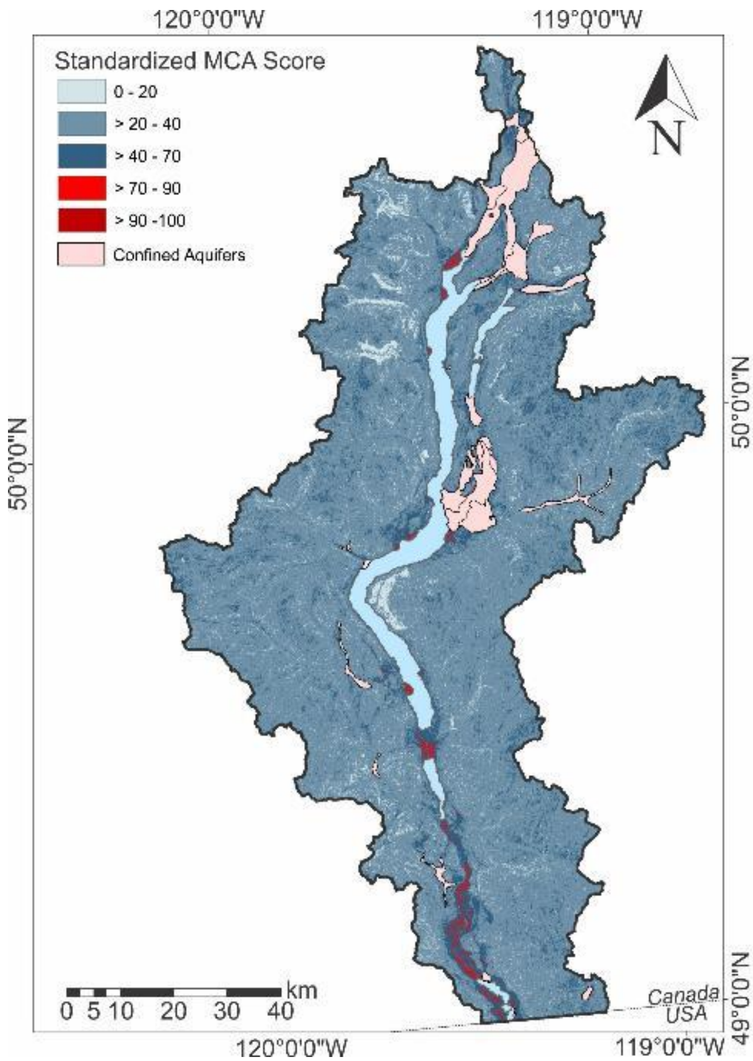

Figure 19: Okanagan unconsolidated MCA results showing the mapped confined aquifers overlapping the areas mapped as 'more likely than not'.

The majority of the areas mapped as 'more likely than not' are also adjacent to lakes in the region. The lakes represent areas of lowest local elevation and in most cases correspond to the end of groundwater flow paths allowing for a greater difference in head from the start of the groundwater flow paths. In the conceptual models (topography- and geologically-controlled), flowing artesian conditions are typically present in these locations.

A few areas in the Okanagan unconsolidated context are mapped as 'more likely than not', yet do not have any flowing wells. Notably the strip mapped as 'more likely than not' in the southern Okanagan that stretches from the Canada/USA border north through the Town of Oliver (Figure 17 and Figure 18). Interestingly, there is no mapped confining unit present. Therefore, the high standardized values for each of the other factors (see Table A12) are causing a higher standardized MCA score. Specifically, elevation, slope and topographic wetness index were each largely contributing high standardized scores in the weighted linear equations. These factors are also among the highest weighted factors in the equation. The remaining factors contribute mostly moderate standardized scores to the equation, with the exception of the confining unit factor which only had two binned intervals and contributed a low score to the entire location. The absence of flowing wells along southern Okanagan valley may be related to one or a combination of factors. Notably, southern Okanagan has a dryer climate and therefore likely has less recharge. As a result, groundwater levels may be lower, meaning that even in discharge areas, it is less likely for the water levels to be above ground level. Groundwater levels may also be influenced by water abstractions, particularly around the Town of Oliver. Finally, the unconsolidated aquifers in the valley bottom are unconfined and likely exists in hydraulic connection with the Okanagan River and lakes, so the groundwater level is largely controlled by the level of Okanagan River and lakes.

Flowing wells in the Okanagan unconsolidated context have similar mean depths as the non-flowing wells, but the non-flowing wells have a much greater maximum depth (Table 10). In this case, the mean and the geomean are not consistent with each other. Almost 50% of non-flowing wells occur within 20 mbgs (Figure 20). Flowing wells have a distribution with higher percent frequencies occurring over a greater range of depths. This indicates that the geomean depths are the more accurate statistical representation, and therefore flowing artesian conditions are more likely to be encountered at greater depths. Flowing wells have higher percent frequencies than non-flowing wells at depths 20–80 mbgs, while non-flowing wells have higher percent frequencies at depths greater than 80 mbgs, but these are overall low occurrences (Figure 20).

Table 10: Depth statistics for flowing and non-flowing wells for the Okanagan unconsolidated context.

	Flowing Wells	**Non-Flowing Wells**
Count	408	6003
Minimum Depth (mbgs)*	2	0.3
Maximum Depth (mbgs)	166	577
Mean Depth (mbgs)	37	42
Geomean Depth (mbgs)	30	21
Median Depth (mbgs)	32	21
Standard Deviation (mbgs)	22	50

* Wells with a depth of 0 were excluded from the results (6 flowing, 226 non-flowing)

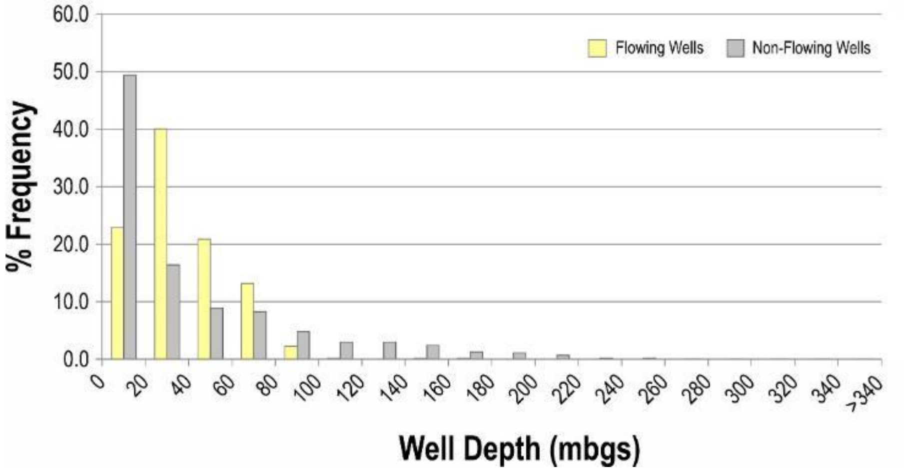

Figure 20: Percent frequency distribution of flowing and non-flowing well depths for the Okanagan unconsolidated context. Units in metres below ground surface (mbgs).

5.3 Fraser Valley Unconsolidated Context

Flowing wells in the Fraser Valley unconsolidated context occur mostly within areas mapped as 'more likely than not' (red areas in Figure 21 and Figure 22). For example, in the west of the study area the flowing wells are quite well contained within the predominately red areas of the Fraser Lowlands, specifically in the Nicomekl-Serpentine valley. In the east, however, the southern Chilliwack-Sumas valley region has a large area that is predominantly red but has a low flowing well occurrence; there are a few sporadic flowing wells in the Chilliwack-Sumas valley. This region is mapped as 'more likely than not' because the factors share many common values with areas in the west that are similarly mapped as 'more likely than not', i.e., they are both flat, have low elevation, are overlain by a confining unit, and have similar stream densities. Of possible relevance is the fact that the Sumas Prairie was once a lake (Sumas Lake). The lake was drained in 1925 with the completion of the Vedder Canal and Sumas Pump Station. As well, 40 km of flood protection dikes were also built at the time. The median depth of reported wells in Sumas Prairie is only 9.1 m (compared to 79.3 m in the Nicomekl-Serpentine) and land reclamation may have altered the natural hydrogeological conditions to a degree that flowing wells (at least at these relatively shallow depths) are not likely to occur. A few flowing wells occur along the northwestern edge of Vedder Mountain and may be controlled by factors associated with the bedrock, which was not mapped in the Fraser Valley.

The greater weight of the stream factor (relative to the other factors) in the Fraser Valley unconsolidated context results in the map having areas mapped as 'more likely than not' (red cells) concentrated around streams. This results in the map having string-like zones mapped as 'more likely than not' in locations where all other factors remain relatively constant.

Flowing wells in the Fraser Valley unconsolidated context generally occur deeper than their non-flowing counterparts (Table 11). Flowing wells are consistently 'more likely than not' to occur (higher percent frequencies) at depths greater than 60 mbgs (Figure 23). This indicates that the deeper a well is drilled, the higher possibility that flowing artesian conditions will be encountered. This could be particularly important in areas mapped as 'more likely than not'. Non-flowing wells occur infrequently at significant depths relative to flowing wells. Despite this much greater range in well depths, flowing wells have a greater standard deviation in their depth occurrence and can still occur at depths shallower than 60 mbgs (Figure 23).

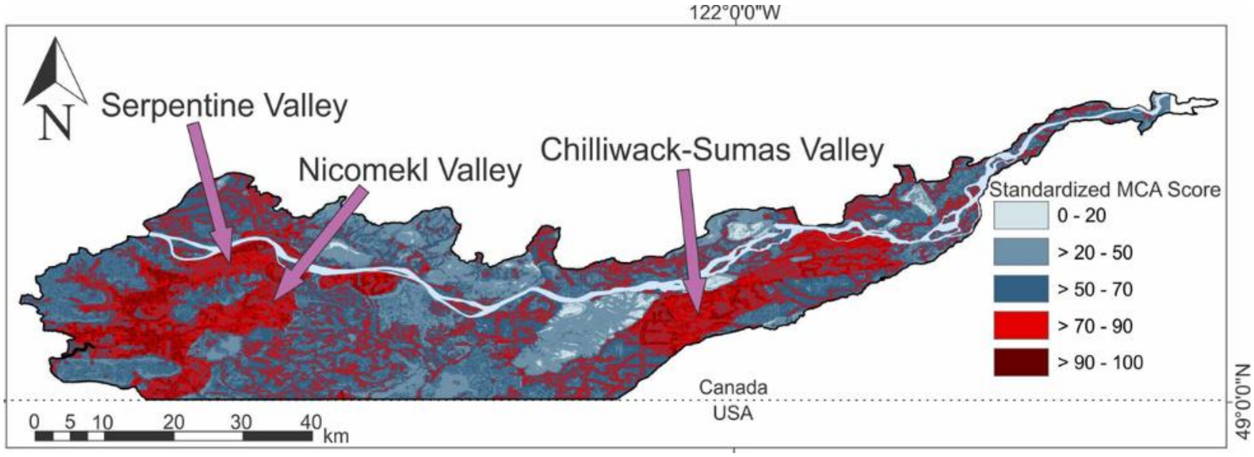

Figure 21: Fraser Valley unconsolidated MCA map. Red cells indicate where flowing wells are 'more likely than not' to occur and blue cells indicate where non-flowing wells are more likely to occur.

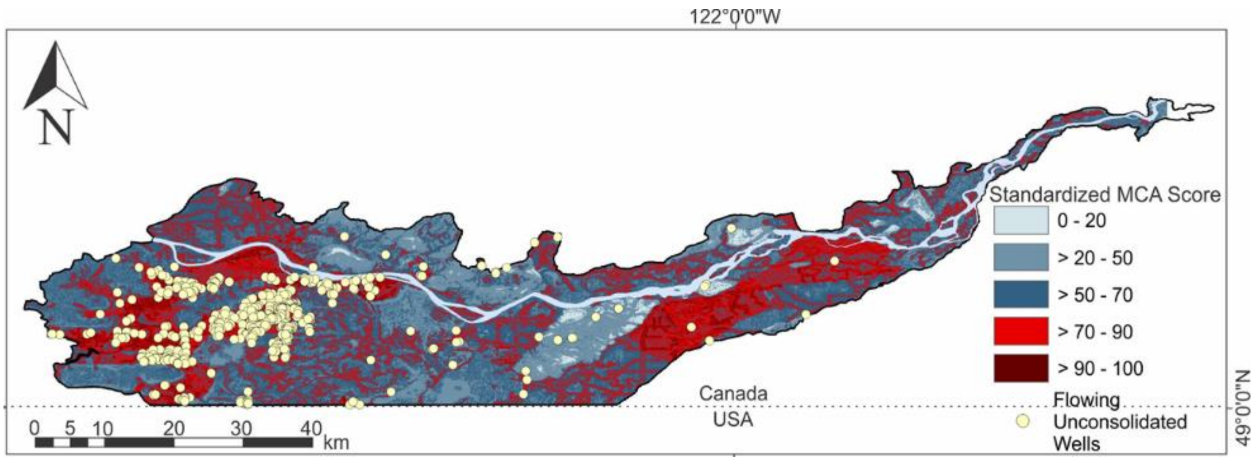

Figure 22: Fraser Valley unconsolidated MCA map showing the locations of flowing wells in unconsolidated materials. Red cells indicate where flowing wells are 'more likely than not' to occur and blue cells indicate where non-flowing wells are more likely to occur.

Table 11: Depth statistics for flowing and non-flowing wells in the Fraser Valley unconsolidated context.

	Flowing Wells	Non-Flowing Wells
Count	785	15904**
Minimum Depth (mbgs)*	0.5	0.3
Maximum Depth (mbgs)	370	1750
Mean Depth (mbgs)	63	35
Geomean Depth (mbgs)	51	22
Median Depth (mbgs)	58	25
Standard Deviation (mbgs)	41	37

* Wells with a depth of 0 were excluded from the results (25 flowing, 764 non-flowing)
**One well excluded from depth statistics as an outlier.

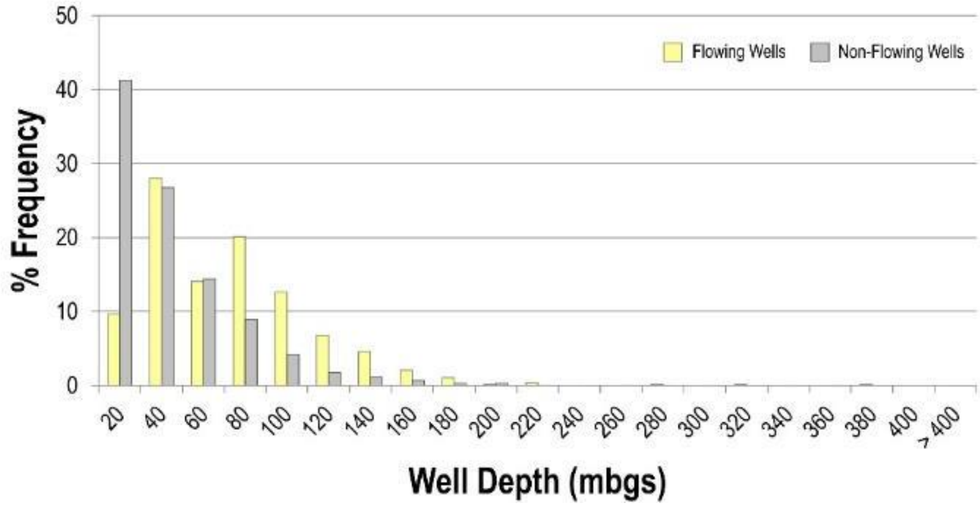

Figure 23: Percent frequency distribution of flowing and non-flowing well depths for the Fraser Valley unconsolidated context. Units in metres below ground surface (mbgs).

5.4 Influential Factors

Section 4.5 presented the weighting for each factor in each hydrogeologic context (Table 5). These weights represent how important each factor is relative to the other factors in each context. The weighting for each factor varies in each context as does the factors which were found to be influential.

5.4.1 Okanagan Bedrock

In the Okanagan bedrock context, slope, flow accumulation, and kernel densities for lineament sets 1 and 3 are the highest weighted factors. Flowing wells in the Okanagan occur most frequently at slopes of between 6 – 18° and their occurrence drops off sharply at greater slope angles (Figure D1), although the highest standardized raster score is for slopes between 10–14° (Table A11). Flowing wells occur mostly at the mid range flow accumulations values (1-100) and the highest standardized raster score is between 1-10 (Table A11). The third most highly weighted factors in the Okanagan bedrock are lineament kernel densities 1 and 3. Flowing wells occur most frequently at mid-range densities for both lineament sets. Lineament set 1 occurs most frequently at densities of 20–40 m/m^2 (Figure D3), which is also the range of the highest standardized raster scores (Table A11). Lineament set 3 has flowing wells occurring most frequently between densities of 20–30 m/m^2 (Figure D3), which is also the range of the highest standardized raster scores (Table A11).

5.4.2 Okanagan Unconsolidated

In the Okanagan unconsolidated context, elevation, slope, TWI, soil drainage and presence of a confining unit are all equally weighted as the highest weights. Flowing wells occur most frequently between elevations of 200–400 masl (Table A12; Figure D4). Flowing wells occur most frequently at low slopes ranging from 0–4° (Figure D4; Table A12) and at moderate TWI values (6-8; Figure D4; Table A12). Flowing wells occur most frequently in areas of poorly and well drained soils, but only in poorly drained soils do flowing wells occur more frequently (3x) than non-flowing wells (Figure D4; Table A12). Finally, flowing wells are more than twice as likely to occur if there is a confining unit present (Figure D6).

5.4.3 Fraser Valley Unconsolidated

In the Fraser Valley all factors (elevation, slope, TWI, stream proximity, soil drainage, and presence of a confining unit) are weighted equally (16%), except flow accumulation (2%). The vast majority of flowing wells occur at low elevations, approximately 85% occur at elevations < 50 masl (Figure D7; Table A13). Flowing wells occur most frequently at low slopes, but only occur more frequently than non-flowing wells at slopes < 2° (Figure D7; Table A13). TWI values between 6–8 are the only bin where flowing wells are greater than non-flowing wells and are almost triple the percent frequency of the other bins (Figure D8; Table A13). Flowing wells are 'more likely than not' to occur within 200 m of a stream (Figure D9; Table A13). Areas with poorly drained soils have the highest occurrence of flowing wells, but imperfectly, areas with poorly and very poorly drained soils have higher occurrences of flowing wells than non-flowing wells. Lastly, flowing wells are 'more likely than not' to occur if there is a confining unit present compared to where a confining unit is absent (Figure D9; Table A13).

6. CASE STUDIES

This section provides site specific examinations of a few select areas that are mapped as 'more likely than not' to have flowing wells in each study area. The sites are viewed in conjunction with well drilling advisories and provide insight and recommendations for advisories where none exist. The case studies are evaluated with either two-dimensional or three-dimensional (2D or 3D) conceptual models of the area. Two models were developed using the Leapfrog geologic modelling software (Seequent, 2019) due to the large number of wells that were used to explore the stratigraphy.

The Okanagan bedrock case study examines the town of Naramata using a vertical 2D conceptual model. Vernon Creek is used as a case study for an Okanagan unconsolidated context by comparing the MCA results to the current well drilling advisory. Armstrong is additionally used to examine the MCA results for the Okanagan unconsolidated context using a Leapfrog model. Finally, in the Fraser Valley unconsolidated context, Aquifers 33 and 58 are examined using a Leapfrog model. The locations of these case studies are presented in Figure 24.

6.1 Overview of Flowing Well Advisories

The B.C. Ministries of FLNRORD and ENV publish Well Drilling Advisories for flowing artesian conditions in areas where flowing wells are known to have a high occurrence. These advisories are intended to aid drillers in determining whether they might encounter flowing artesian conditions. There are seven flowing well advisories across the province, five of which are within the study areas. The Okanagan has well drilling advisories for Westwold (Province of B.C., 2018a), Vernon Creek (Province of B.C., 2018c), Coldstream (Province of B.C., 2018b), and Lower Mission Creek area of Kelowna (Province of B.C., 2017c). The Fraser Valley has a single flowing well advisory for Surrey and Langley (Province of B.C., 2018d). The locations of these advisories are identified on Figure 24. The flowing well advisories identify flowing well locations and, in some cases, outline the extent of the flowing artesian conditions with the outline of the aquifer the wells are completed in. The advisories also provide a brief background on flowing wells and why they occur, as well as the how drillers can prepare in case flowing artesian conditions are encountered.

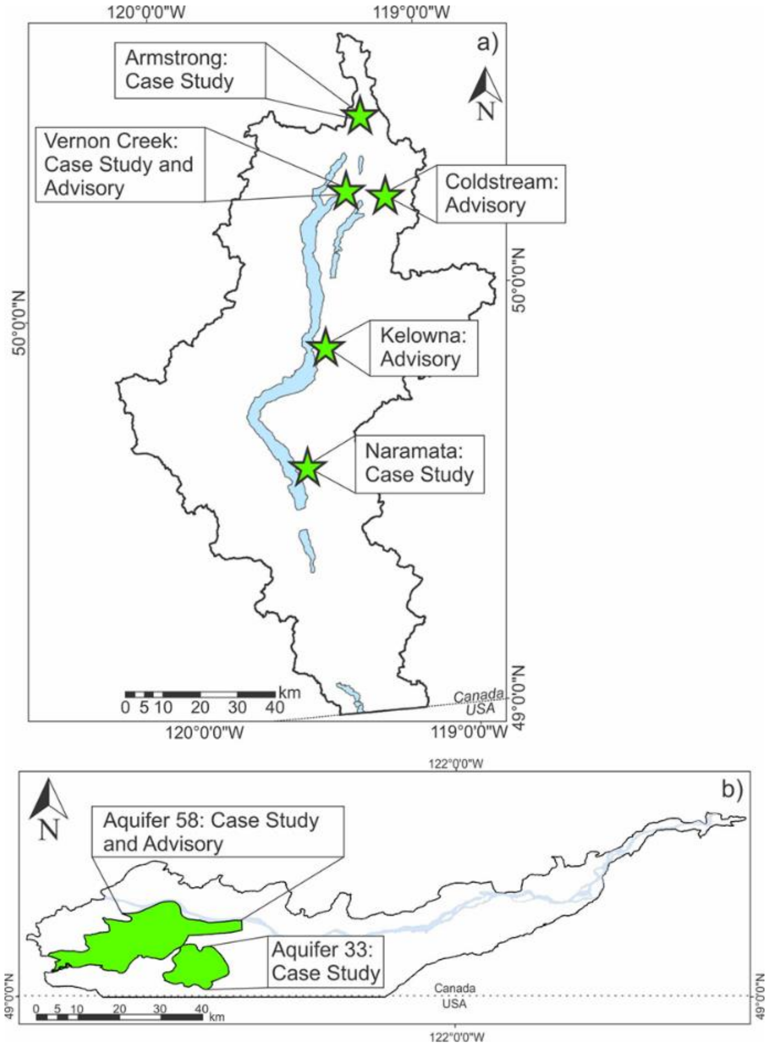

Figure 24: Map of case study areas and flowing well advisory locations in a) Okanagan Basin and b) the Fraser Valley.

6.2 Okanagan Bedrock

6.2.1 Naramata

The community of Naramata was used to examine and assess flowing wells in a bedrock context, particularly how flowing conditions may be related to fractures. The Naramata region is underlain by a low productivity fractured bedrock aquifer (Aquifer 298) that hosts a number of flowing wells. The community of Naramata predominately resides on an alluvial fan deposit and a terrace bench. All of the flowing wells in the region are bedrock wells and tend to cluster around the perimeter of the alluvial fan deposit (Figure 25: B-B'). Interestingly, there are several non-flowing bedrock wells located adjacent to flowing bedrock wells in Naramata, which suggests there may be distinctly different potentiometric levels in the fractured bedrock encountered by wells in proximity to each other.

Flowing wells in Naramata have reportedly been an issue in the region. In January 2019, the consulting company Tetra Tech issued a report to the Ministry of Transportation and Infrastructure concerning drainage issues in the Naramata region. This report details an anecdotal account from a local resident regarding a flowing well (Tetra Tech, 2019). The report identifies an unconfirmed report from a resident that a flowing well may have been improperly decommissioned by digging a trench, filling it with gravel and allowing water to flow through this trench, which the resident estimated to be under the new railway (Tetra Tech, 2019). The Tetra Tech report does not identify the Well Tag Number of the well. The information on the allegedly improperly decommissioned well outlined in the Tetra Tech report is currently under review and investigation by FLNRORD. Indeed, there are four flowing wells on the property in the GWELLS database. These four wells consist of the flowing wells used to create the conceptual model presented in this section.

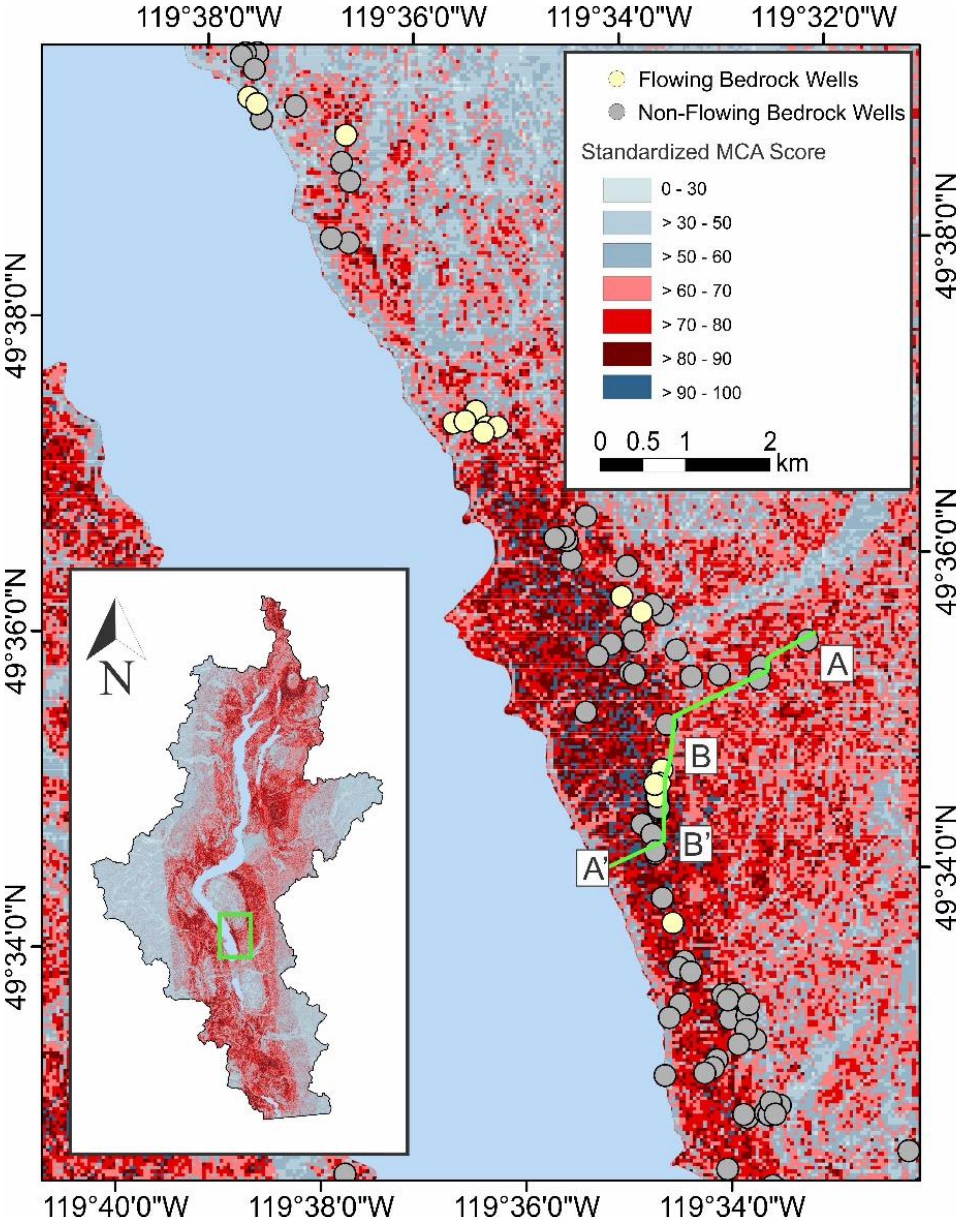

Figure 25: Okanagan bedrock context MCA mapping results in the Naramata region showing flowing and non-flowing bedrock wells. The inset map shows the extent of Naramata (green rectangle). The green line represents the transect for the 2D conceptual model (Figure 26).

Naramata has a relatively large cluster of flowing bedrock wells (Figure 25), although there are more non-flowing wells than flowing wells (84 vs 16; Table 12). Flowing and non-flowing wells in Naramata are co-located through the region. The statistics provided in Table 12 reflect the broader Naramata region and more local scales may not necessarily follow the same trends (e.g., wells along the B-B' transect). Flowing wells in Naramata are on average shallower than their non-flowing counterparts and have a median depth of 79 mbgs. Non-flowing wells have a median depth of 98 mbgs; however, the flowing wells occur over a greater range of depths and have a smaller standard deviation.

When bedrock is fractured, the fractures can act as conduits for groundwater flow. The relatively impervious bedrock matrix effectively acts as a confining unit for the fractures. Due to the high lineament density values surrounding Naramata (see Figure B6 to Figure B11) it is likely that the lineaments represent an interconnected fracture network. These fractures are exposed at higher elevations where the Quaternary sediment is sparse allowing for a recharge area with high hydraulic head.

Table 12: Depth statistics for flowing and non-flowing wells in Naramata (area shown in Figure 25) for the Okanagan bedrock context.

	Flowing Wells	**Non-Flowing Wells**
Count	16	84
Minimum Depth (mbgs)	37	15
Maximum Depth (mbgs)	146	227
Mean Depth (mbgs)	82	104
Geomean Depth (mbgs)	77	92
Median Depth (mbgs)	79	98
Standard Deviation (m)	30	42

A vertical 2D conceptual model for flowing artesian conditions in fractured bedrock is shown in Figure 26. The water levels for each well were obtained from GWELLS. The conceptual model suggests there are at least two distinct potentiometric levels in the area between B and B' – one above or close to ground surface that results in flowing wells, and one at greater depth, approximately 20 m below ground surface, that does not result in flowing wells. At this location, there are only minor differences in lithology, well depth, and the depth of water bearing fractures among these wells. This suggests a possible fracture control, whereby wells with a higher potentiometric surface are simply intersecting a fracture(s) that originate at higher elevation.

No Well Drilling Advisory currently exists for Naramata. While Naramata only has 16 flowing wells, these wells account for 13% of flowing bedrock wells in the Okanagan study area. While these 16 wells are not in a tight cluster, they do represent one of the largest groupings of flowing bedrock wells in the Okanagan Basin. As Figure 26 shows, flowing wells can occur immediately beside non-flowing wells of the same depth. Therefore, when drilling in fractured bedrock in this area there is an equal risk encountering flowing artesian conditions as not, even though the local area has been mapped a 'more likely than not'.

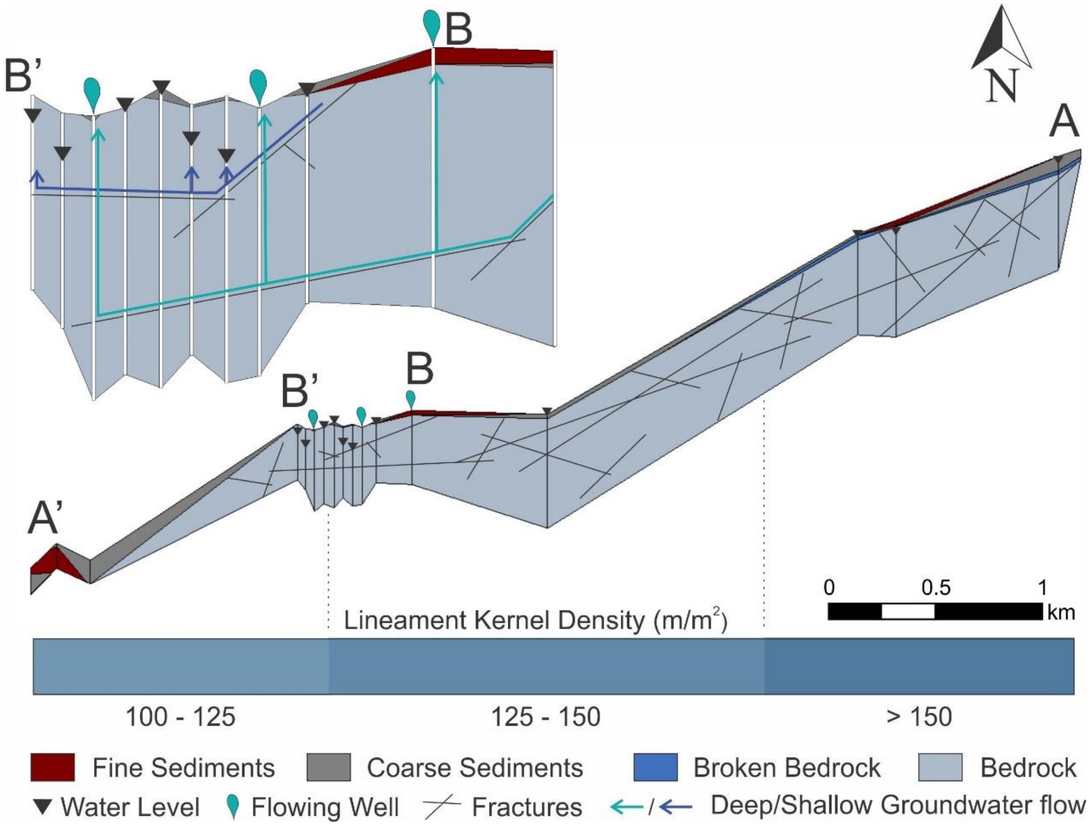

Figure 26: Two-dimensional (2D) conceptual model of flowing bedrock wells in Naramata. Lineament kernel density values determined in Figure B7 are shown along the bottom of the figure. The larger scale inset shows conceptual groundwater flow paths in the fractures which would lead to flowing and non-flowing wells. The model is constrained by ground surface elevation and the depth of the wells (2x vertical exaggeration).

6.3 Okanagan Unconsolidated

6.3.1 Vernon Creek

Vernon Creek is an area south of the City of Vernon that borders Okanagan Lake. The location currently has a Well Drilling Advisory, which indicates that flowing wells can occur in the valley bottom, not only in the unconsolidated sediments but in the bedrock as well (Province of B.C., 2018c). The advisory showcases the location and depths of the flowing wells in the vicinity of Vernon Creek and indicates the likely extent of flowing artesian conditions. While the entire area is mapped as having a confined aquifer, the confining units in the valley are discontinuous and therefore the extent of flowing artesian conditions may not be pervasive throughout the entire valley (Province of B.C., 2018c).

Figure 27 shows the MCA results for Vernon Creek. The MCA results for Vernon Creek are consistent with the findings from Section 5, which indicated that the MCA maps accurately portray the extent of flowing artesian conditions. The flowing wells tend to occur in areas mapped as 'more likely than not' while non-flowing wells tend to cluster around the outer edges of these area. The extent of the areas mapped as 'more likely than not' (red cells in Figure 27) does not account for discontinuities in the confining unit as noted above, and therefore provides a conservative representation of flowing artesian conditions.

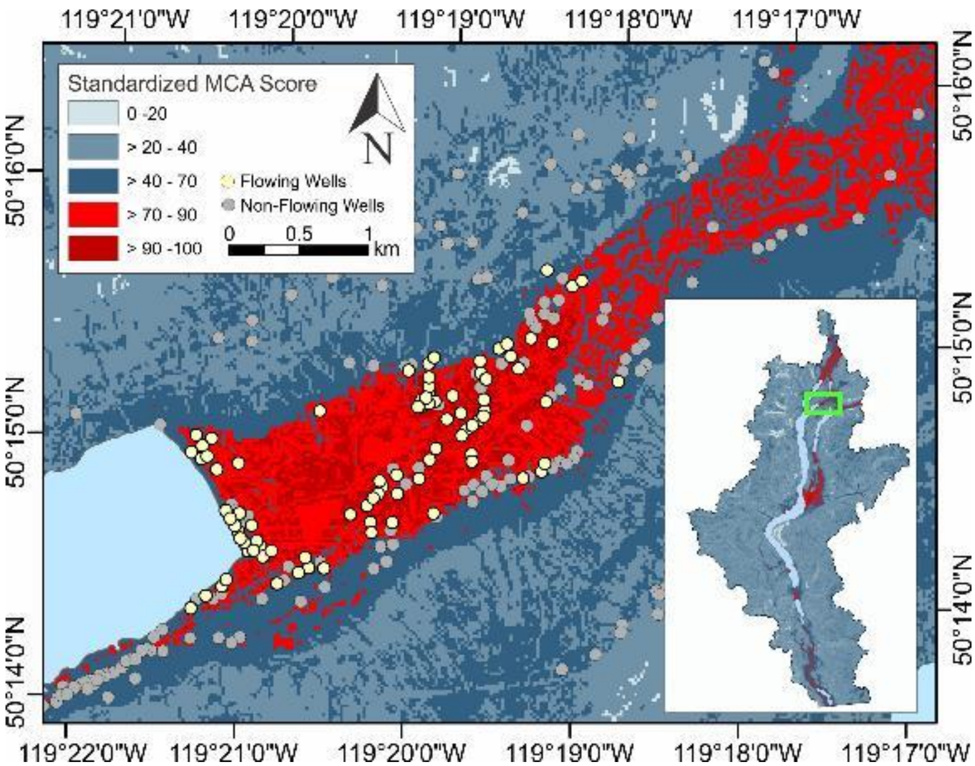

Figure 27: Okanagan unconsolidated context MCA map results in the South Vernon region with flowing and non-flowing wells in unconsolidated materials. The inset map shows the extent of South Vernon (green rectangle).

Flowing wells in Vernon Creek can occur at range of depths and also have a deeper median depth than non-flowing wells (49 vs 10 mbgs), a similar maximum depth (113 vs 128 mbgs), and a lower standard deviation (Table 13). Due to the lateral extent and variety of depths that flowing wells can occur at in Vernon Creek, it should always be assumed that flowing artesian conditions will be encountered when drilling.

Table 13: Depth statistics for flowing and non-flowing wells in South Vernon (area shown in Figure 27) for the Okanagan unconsolidated context.

	Flowing Wells	Non-Flowing Wells
Count	88	123
Minimum Depth (mbgs)	2	2
Maximum Depth (mbgs)	113	128
Mean Depth (mbgs)	45	23
Geomean Depth (mbgs)	38	13
Median Depth (mbgs)	49	10
Standard Deviation (m)	21	26

Because the flowing wells in Vernon Creek occur in a confined aquifer, the flowing artesian conditions are largely geologically-controlled; however, topography also appears to play a role. For example, the area mapped as ‘more likely than not’ (red cells) outlines a valley bottom that slopes westward (Figure 27). The elevation of the valley bottom is ~350 masl near Okanagan Lake in the west and ~370 masl in the east. Presumably, groundwater is discharging into Okanagan Lake at the western edge, so the hydraulic gradient likely has an upward component. The lower likelihood areas mapped in blue represent the ridges flanking the valley bottom and have elevations of ~600 masl.

6.3.2 Armstrong

The City of Armstrong is located in the northern tip of the Okanagan Basin. The case study area extends from Okanagan Lake northwards, encompassing Armstrong and the surrounding area (Figure 28). Note that in Figure 28 only the eastern portions of Aquifers 102 and 1150 are included, and Aquifers 1154, 1155 and 1156 are shown as single polygon due to their similar extent. Flowing wells in the area occur in bedrock and unconsolidated materials, but the MCA map for the Okanagan unconsolidated is used for comparison. However, both bedrock and unconsolidated wells were used for the Leapfrog geologic modelling, which is discussed below. This case study is used to examine the importance a confining unit plays in determining the extent of flowing artesian conditions.

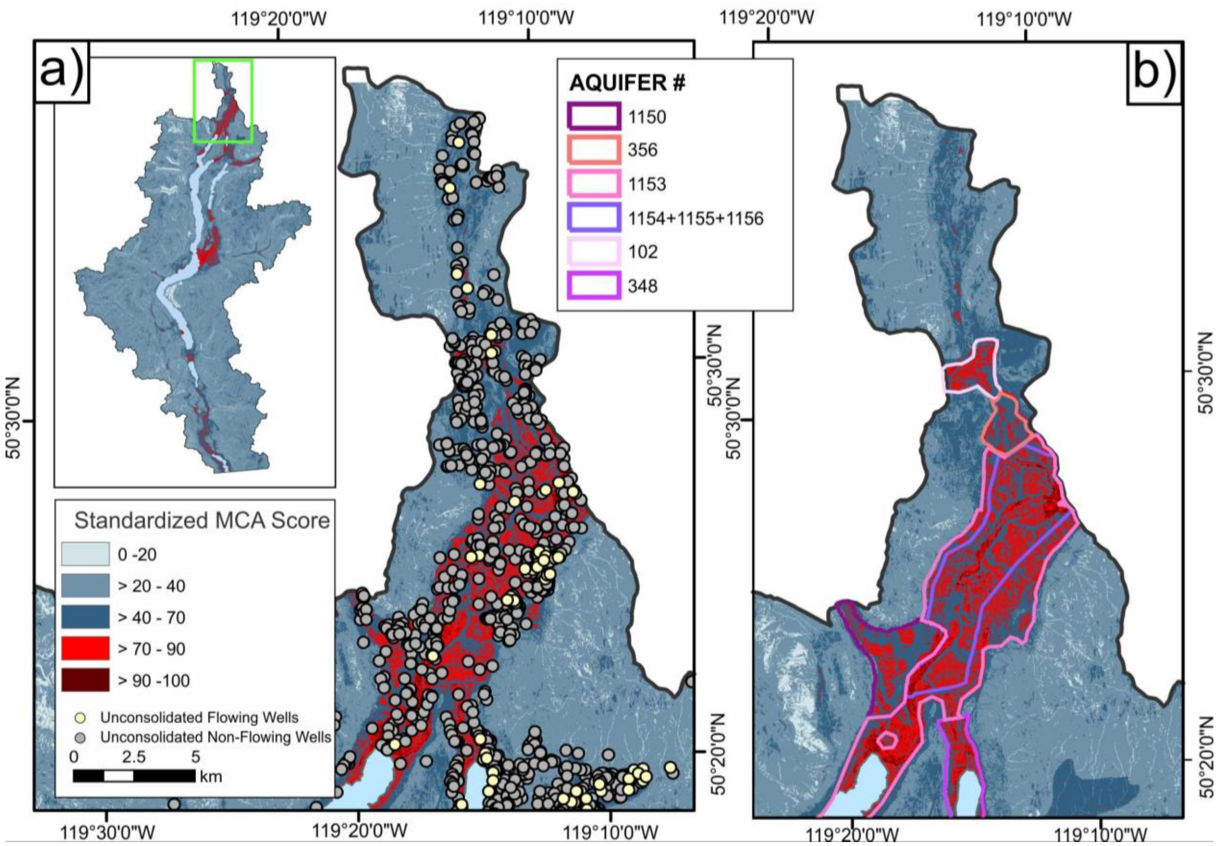

Figure 28: Armstrong MCA map for Okanagan Basin unconsolidated context. Confined aquifer #'s are listed from North to South. Note: only the eastern portions of Aquifers 102 and 1150 are shown. One Aquifer polygon is presented for 1154, 1155, and 1156 due to their similar extent.

There are 11 flowing bedrock wells and 42 flowing wells in unconsolidated material (Table 14). The bedrock wells (not shown in Figure 28) occur throughout the study site but generally occur around the outer margins of the confined aquifers in the area. The majority of the unconsolidated flowing wells occur within the extent of the mapped confined aquifers, with the exception of four wells in the northern part of the study area that lie outside the extent of the mapped confined aquifers but still within small areas mapped as 'more likely than not' (red cells) (Figure 28). This northern area is mapped largely as having low likelihood (mostly blue cells) because there are no mapped confined aquifers and no other topography-related factors that are associated with flowing artesian conditions.

Unconsolidated flowing wells in the Armstrong area tend to be deeper, with a greater median depth than their non-flowing counterparts (Table 14). Bedrock flowing wells have a shallower median depth than their non-flowing counterparts but are deeper than the unconsolidated flowing wells.

Table 14: Depth statistics for flowing and non-flowing wells in Armstrong (area shown in Figure 28) for wells in bedrock and unconsolidated materials. Units for depths are metres below ground surface (mbgs).

	Unconsolidated		**Bedrock**	
	Flowing Wells	**Non-Flowing Wells**	**Flowing Wells**	**Non-Flowing Wells**
Count	41	616	9	105
Minimum Depth (mbgs)	2	2	26	4
Maximum Depth (mbgs)	94	577	183	273
Mean Depth (mbgs)	49	57	94	91
Geomean Depth (mbgs)	36	34	82	75
Median Depth (mbgs)	52	47	79	85
Standard Deviation (mbgs)	28	52	52	53

A 3D geological model was built in Leapfrog to assess the potential extent of the confining unit. The lithologies from the GWELLS database had been previously standardized (see Allen et al., 2008). For this study, these lithologies were further classified as bedrock, sand, clay, glacial, gravel and overburden. Glacial and overburden are terms used in the database that do not have strict definitions. The term overburden was assigned to a variety of lithologies such as 'topsoil' and 'fill' and is used to refer to any surficial material that does not fit into the other lithologies. Glacial is not as easily defined as it can have many meanings (glaciolacustrine, till, glaciomarine, glaciofluvial, etc.). The lithologies in the wells database are generally reported by water well drillers who may not have significant training in sediment classification, nor do they focus on describing in detail non-water-bearing sediments. Therefore, it is assumed that 'glacial' refers to till, as till is a common unit identified by drillers in B.C. Till is an unsorted sediment, which is usually compacted, containing fines and so would function as a confining unit. However, glacial was assigned as its own lithology, even though it is assumed to represent till. This glacial lithology is not extensive throughout the study area. All other materials that could potentially act as confining units, including predominately silt and/or clay, were assigned a clay lithology to represent the confining unit at the site. All wells with standardized lithological data were imported into the model.

Figure 29 shows the extent of the modelled confining unit (clay) with the mapped confined aquifers superimposed. The confined aquifers include 102, 348, 349, 356, 1150, 1153, 1154, 1155, 1156 from GWELLS; note that only the eastern portions of Aquifers 102 and 1150 are included, and Aquifers 1154, 1155 and 1156 are shown as single polygons due to their similar extent. The four flowing wells of interest (Figure 29) lie just to the north of the area investigated by Golder Associates (2017) in regard to the Hullcar Aquifer (102) and similarly by Stewart and Allard (2017) in the North Okanagan aquifer mapping and geological modelling study. The Leapfrog model by Stewart and Allard (2017) for this area terminates at the eastern extent of Aquifer (102). The area immediately to the north was the focus of this study.

The Leapfrog modelling in this study indicates that the confining unit extends northward into the narrow valley to the north of Aquifer 102. Further south, the confining unit is continuous in the locations where the confined aquifers are mapped, although Stewart and Allard (Figure 10; 2017) identify windows in the confining layer for Aquifer 102. While there may be a topographic control for the flowing wells within the narrow valley north of Aquifer 102, the modelling suggests that there might be a confining unit present.

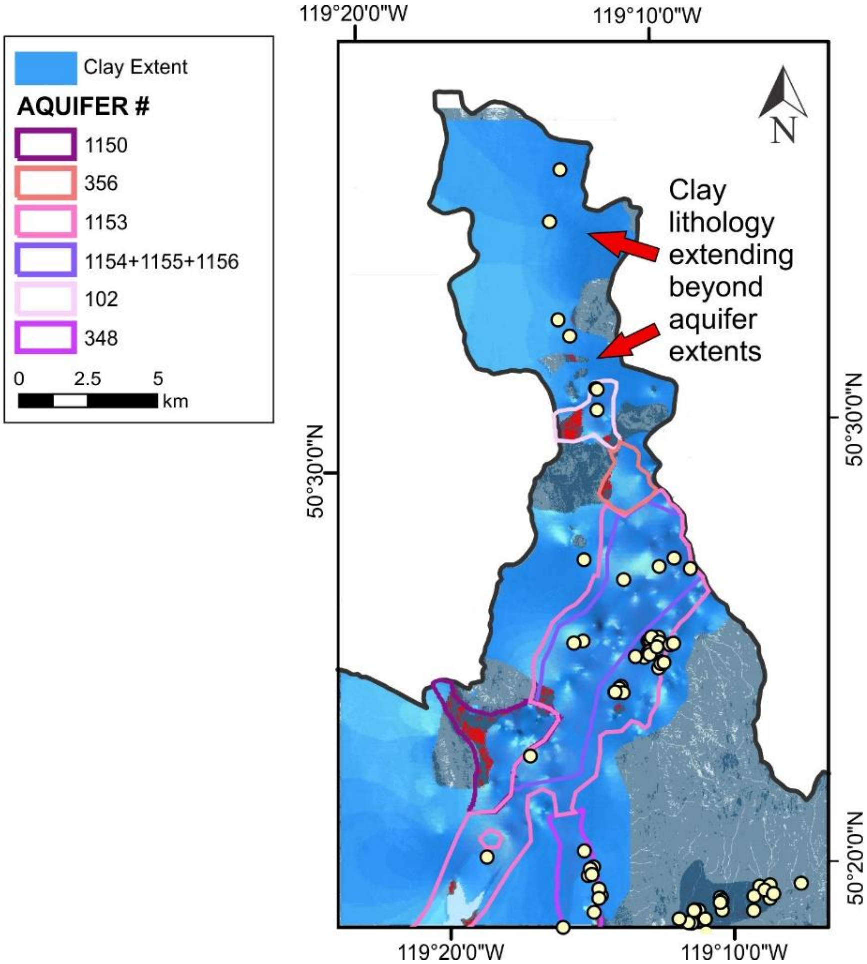

Figure 29: The Leapfrog extent of clay in the Armstrong area with the MCA unconsolidated results showing flowing wells in unconsolidated materials and the outlines of the mapped confined aquifers superimposed. Red arrows indicate the extent of the clay unit beyond the confined aquifers.

6.4 Fraser Valley

6.4.1 Aquifers 58 and 33

The Fraser Valley has one Well Drilling Advisory for the Nicomekl-Serpentine aquifer (Aquifer 58) in Surrey and Langley (Province of B.C., 2018d). The majority of flowing wells in the Fraser Valley occur in this aquifer with 183 flowing wells correlated to the aquifer (Province of B.C., 2021a). Aquifer 58 is a deep (60–150 mbgs) confined sand and gravel aquifer, with a median water depth of 3.05 mbgs (Province of B.C., 2016) and a median well depth of 79.25 mbgs (Province of B.C., 2020a). The advisory uses the extent of Aquifer 58 as the extent of the flowing well advisory (Province of B.C., 2018d). Figure 30 shows the extent of Aquifer 58 and the unconsolidated flowing wells.

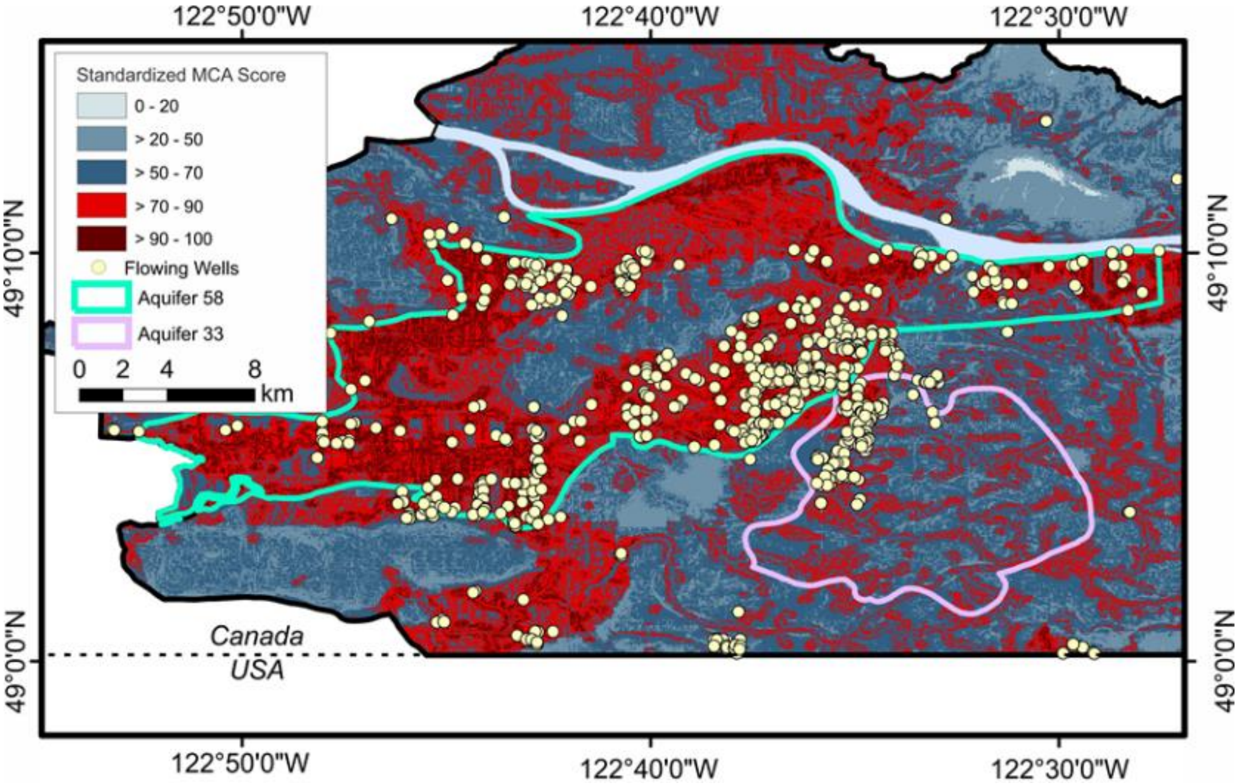

Figure 30: Fraser Valley unconsolidated context MCA map results and flowing wells for the area encompassing Aquifer 58 (pale green) and Aquifer 33 (pink).

Aquifer 33 (the West of Aldergrove Aquifer) is also a confined sand and gravel aquifer (Figure 30). The Province shows 97 flowing wells correlated to the aquifer (Province of B.C., 2021b), and there are 30 flowing wells that are within the extent of the aquifer but are not correlated to it. Aquifer 33 is shallower than Aquifer 58 (~30–70 mbgs) but has a deeper median water depth of 25.15 mbgs (Province of B.C., 2021b). Aquifer 33 is an inter-till aquifer with two permeable units that slope westward and merge into a single unit in the west (Province of B.C., 2021b).

The MCA results for the Fraser Valley unconsolidated context (see Figure 21) shows concentrated areas mapped as 'more likely than not'; for example, the area corresponding to Aquifer 58 (Figure 31). The areas mapped as 'more likely than not' flank the outer perimeter of Aquifer 58 and represent the Serpentine Valley (Northwest) and the Nicomekl Valley (South). Flowing wells in Aquifer 58 are more concentrated in the southern portion of the aquifer (i.e., the Nicomekl Valley) and these flowing wells occur consistently within the areas mapped as 'more likely than not' (red cells), while the non-flowing wells tend to occur in the lower likelihood areas (blue cells). Areas within Aquifer 58 that are mapped as 'more likely than not' are generally at low elevation and low slope angle. This highlights the importance of considering multiple factors to determine the extent of flowing artesian conditions.

Flowing wells in Aquifer 33 are limited to the northwestern extent of the aquifer (Figure 30). The majority of Aquifer 33 is mapped as low likelihood (i.e., blue cells); however, the northwestern portion is mapped as 'more likely than not' (although, the red cells are hidden by the wells themselves). This indicates that the MCA results were accurately able to determine the approximate extent of the flowing artesian conditions in the aquifer, but the cause of the limited extent is not immediately apparent. Interestingly, the boundary of the area mapped as 'more likely than not' generally corresponds with the change in relief from the surrounding highlands. This relief change is not as pronounced as it is in Vernon Creek in the Okanagan, but it could indicate topographic control on the flowing artesian conditions. The occurrence of flowing wells in this aquifer was explored further in Leapfrog.

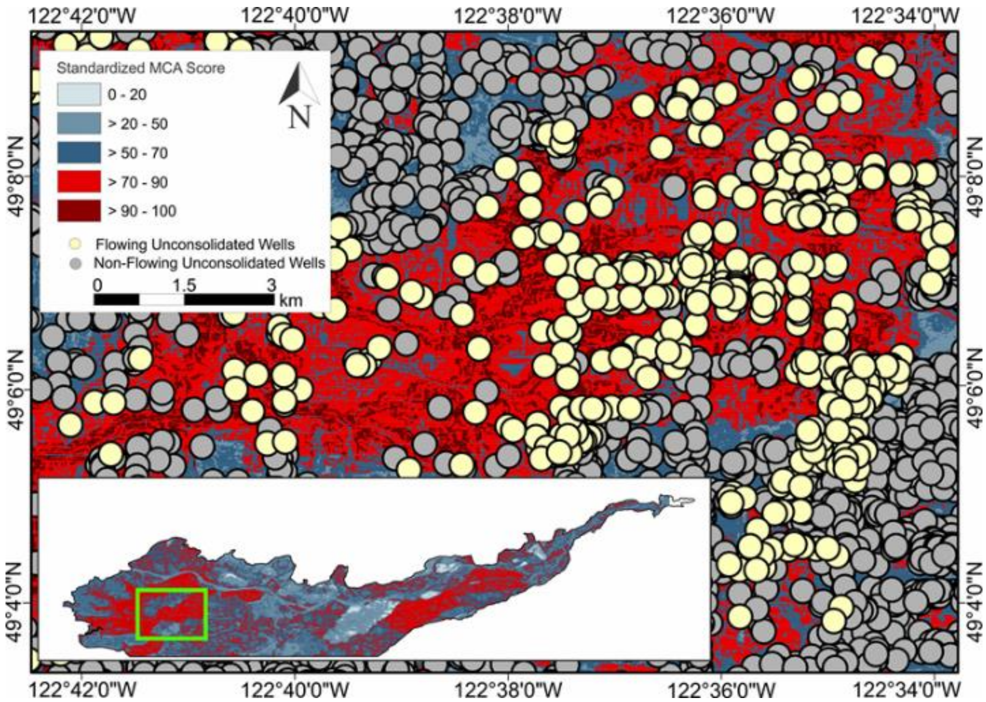

Figure 31: Fraser Valley unconsolidated context MCA map results in a portion of the Nickomekl Valley (from Aquifer 58) showing flowing and non-flowing wells in unconsolidated materials. The inset map shows the extent of the map in the Fraser Valley (green rectangle).

A Leapfrog model was built to examine flowing artesian conditions within Aquifer 33, because this aquifer does not have a Well Drilling Advisory. The main focus was on examining the extent of the confining unit as represented by glacial and clay lithologies. Aquifer 33 has over 2000 groundwater wells within its lateral extent (but not all of these wells are correlated directly to the aquifer), all with varying quality of lithological data. A small subset of wells (48) was used to construct the model. The 48 wells were chosen based on quality of the well lithology log and position along five transects across the aquifer. The same standardized lithology database previously used in the Armstrong model was used for this model, and the lithologies were reclassified to clay, glacial, sand, gravel and overburden. Similar to the Armstrong Leapfrog model, the glacial lithology is assumed to represent till. This assumption is made for the same reasoning as presented in the Armstrong model, but additionally because Aquifer 33 is defined as an inter-till aquifer and the glacial and clay sediments are interbedded throughout the model. This assumption is believed to be reasonable as the flowing wells mostly appear to be screened in a sand lithology. However, it should be noted that Aquifer 33 is defined as a sand and gravel aquifer, and these sand and gravel units likely represent glaciofluvial sediments.

The Leapfrog model shows glacial and clay layers extending throughout the model (Figure 32). The confining lithologies (clay and glacial) dip westward towards Aquifer 58 (not shown in model). The flowing artesian wells are located along the base of a ridge within the boundary of Aquifer 33 (Figure 32).

This model highlights the importance of not only considering the extent of the confining unit but also other factors such as elevation. The model shows that the confining unit of glacial material and/or clay is present throughout the model area but flowing artesian conditions do not occur until there is a drop in elevation (see DEM in Figure 32b). The confining unit maintains the hydraulic head at a relatively constant level when the elevation drops, resulting in a hydraulic head that is above ground surface. Similar to flowing artesian conditions in Vernon Creek, the Fraser Lowlands are also likely geologically-controlled and topography-controlled.

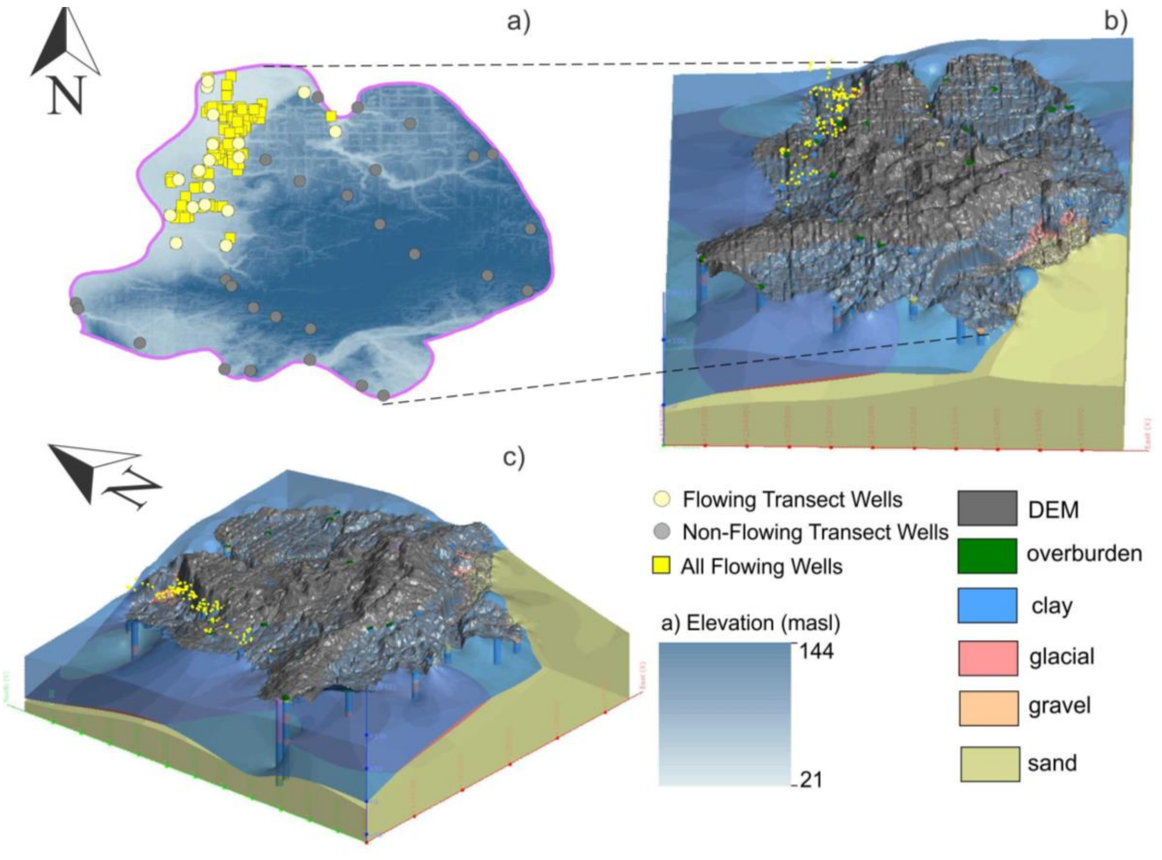

Figure 32: a) DEM of Aquifer 33 with the flowing and non-flowing wells used in the transects (circles) and all flowing wells in the aquifer (squares). b) Leagfrog Geo Model for Aquifer 33 DEM overlay c) Leapfrog model for Aquifer 33 re-oriented.

7. DECISION-SUPPORT TOOLS

Phase 4 focused specifically on meeting objective 4 and involved preparing an information package to support decision-making. In addition to the GIS maps produced through this study and the supporting documentation (i.e., this report), the following tasks were included in the study and are summarized herein:

1) Assisting FLNRORD in documenting current conditions of flowing wells during inspections in the Fraser Valley and the Okanagan.
2) Reviewing information collected during the study to: i) assess how owners of existing flowing wells can comply with s. 53 of the *Water Sustainability Act* (*WSA*), ii) identify the main barriers

affecting compliance with s. 53 and strategies that government can consider to strengthen compliance, and iii) identify where construction standards can be developed in the GWPR or even as best practice to promote s. 52 of the *WSA* (controlling artesian flow during construction).

3) Providing guidance to ENV and FLNRORD for developing area-specific flowing well advisories for land owners and practitioners.

7.1 Documenting Current Conditions during Inspections of Flowing Wells

7.1.1 Additional information related to inspections of flowing artesian wells

In 2020, the project team met with FLNRORD staff from Surrey and Penticton and, together, identified additional information for FLNRORD/ENV's consideration to gather in the field during an inspection of flowing wells. The additional information included describing the state of the flow emanating from the well, where artesian flow was draining to, and the possibility of backflow occurring back down the well. This information can be included in the next update of the Province's Well Inspection Form.

In addition to the field-based information, the team identified additional questions to help decision makers assess the state of the flowing well and inform potential enforcement actions to address uncontrolled artesian flow. These additional questions focussed on the type of aquifer the well is completed in, how the well is designed and constructed, its location, as well as questions related to impact of the uncontrolled artesian flow, and challenges to controlling the flow. The field-based information and additional questions were provided to ENV in a letter dated September 29, 2020 (Appendix E).

7.1.2 Inspections of flowing wells in the Lower Fraser Valley

Section 53 of the *WSA* requires the owner of a flowing well to engage a qualified well driller or professional to stop or control the artesian flow. Between March 9 and 12, 2020, Surrey FLNRORD staff inspected 22 wells in the Surrey-Langley area and Brynje Johnson was able to observe two of the inspections. Note that COVID restrictions were put in place soon after, which limited our ability to participate in other inspections. The purpose of the inspections was primarily to check compliance with s. 53 of the *WSA* (existing flowing wells) and to raise awareness with well owners about the requirement to control artesian flow. Results of the 22 inspections are summarized in Table 15, based on information provided by the Groundwater Protection Officer of FLNRORD. Notably, all inspected wells were drilled into unconsolidated sand and gravel aquifers, and only 10 of the wells (45%) had the flow controlled.

The inspections also revealed that measuring artesian pressure can be a challenge because the different wellhead completions do not allow pressure to be readily measured. Other challenges with older wells include: 1) the well owner has already equipped the well and is using the water, and 2) the nature of well construction may be uncertain, especially if no well record is available.

Table 15: Summary of the results of flowing well inspections carried out by FLNRORD March 9-12, 2020 in the Surrey-Langley area.

No. of wells inspected	No. of domestic wells	No. of non-domestic wells	% of wells where flow is controlled	Comments
22	9	13	45%	All wells were drilled into unconsolidated sand and gravel aquifers.

7.2 Compliance

Part 3 of the *WSA* addresses the Protection of Water Resources. Sections 52 and 53 in Division 3 (Wells and Groundwater Protection) speak to controlling artesian flow during construction of a well and controlling flow in existing flowing wells. Part 8 of the Groundwater Protection Regulation (GPR) under the *WSA* (sections 66, 67 and 68) has additional requirements for stopping or controlling artesian flow and reporting on the management of artesian flow.

To date, drillers and hydrogeologists can review records of nearby wells and consult the available Well Drilling Advisories as part of their pre-drilling assessment to determine the likelihood of encountering artesian conditions. In 2020, Engineers and Geoscientists of B.C. (EGBC) also issued a *Practice Advisory on Flowing Artesian Wells and Excavation* to inform best practices by EGBC members (Engineers and Geoscientists of B.C., 2020). The results of the mapping in this study should further help practitioners prepare for encountering flowing artesian conditions in drilling new wells in the Okanagan Basin and Fraser Valley. Additionally, the maps and advisories could also be used to educate landowners in the study areas about the importance of preparing for flowing artesian conditions.

However, there still remains a high number of existing historic wells that may be flowing without any form of control. Based on discussions with practitioners and well-drillers, we briefly summarize the main options raised by practitioners for controlling flow from existing wells, which may be barriers to compliance for owners of those flowing wells.

Flow from existing wells can potentially be controlled in a number of ways and for a range of costs, depending on the type of aquifer, the artesian head, nature and volume of flow, the state of the well, how the well was originally constructed, and the impact resulting from the flow:

1) Raising casing stick-up: If the artesian head level is not too high above ground surface, it may be feasible to weld on an additional length of production casing above the artesian head level to stop the flow. This is one of the least expensive measures of stopping flow.
2) Installing a well packer or shale trap: For wells drilled into fractured bedrock, installing a well buster or shale trap to limit artesian flow to only the production casing so that artesian flow can be controlled (flow outside of the production casing can not be controlled). If the production casing has been securely seated into bedrock with a surface seal, stopping the flow altogether without any leakage may be possible. However, many of the existing historic flowing wells were not constructed with a competent surface seal. Figure 33 shows a shale trap installed in a bedrock well.
3) Retro-actively grouting in a surface casing: For flowing wells drilled into unconsolidated sediments where there are concerns that leakage may occur around the production casing, it may be possible to retro-actively grout a surface casing into the ground. Flow can then be stopped via the production casing without leakage occurring around the outside of the well casing, so long as the seal makes effective contact against the surrounding sediments and is strong enough to withstand the artesian pressure.
4) Decommissioning the flowing well if flow can not be controlled: In unconsolidated aquifers, decommissioning the flowing well may be achieved by drilling one or more pressure relief well(s) adjacent to the existing flowing well, and pumping the groundwater level down to below ground level to allow the existing well to be decommissioned. This is usually the option if flow can not be controlled in the existing flowing well. The pressure relief well(s) would be designed and constructed to be able to stop and control artesian flow, if necessary. This method requires a professional hydrogeologist to determine the number and location(s) of pressure relief well(s) and to specify the pumping rates, and a professional well driller with the necessary skills to construct the pressure relief well(s) and decommission the existing flowing well. Western Water

Associates Ltd. (2019) reported on their project to decommission a flowing well in Westwold, B.C. with the aid of a pressure relief well.

5) Manage the artesian flow: If the statutory decision maker believes there are exceptional circumstances that prevent artesian flow to be stopped or controlled and that flow from the well does not pose a threat to property, public safety or the environment, then s. 52 (6) of the *WSA* allows the flow to be managed in accordance the direction of the decision maker. This option requires an application to the decision maker and a technical assessment by a professional consultant. Schedule 1 of the GPR outlines the information required by the decision maker. The Province of B.C. (2020c) has also developed an operational policy to support the statutory decision maker in applying s. 52 (6).

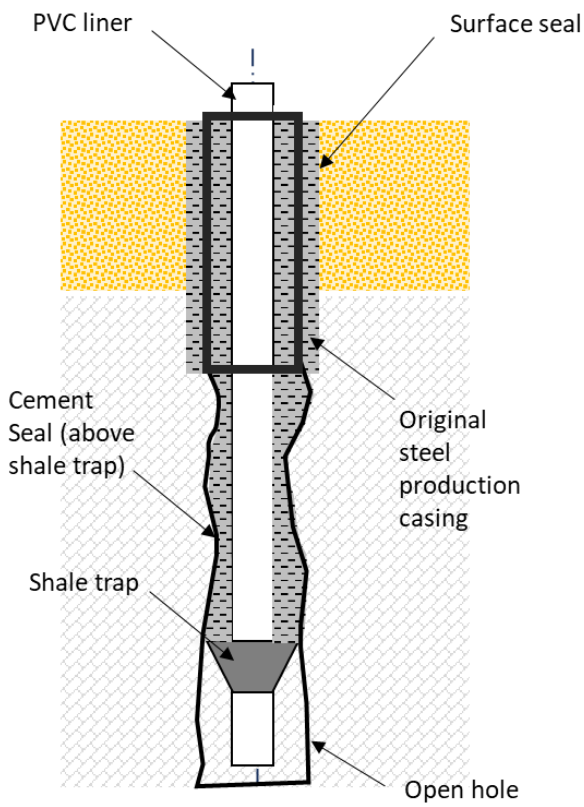

Figure 33: Schematic of a shale trap installed in a bedrock well.

7.2.1 Challenges to Compliance

One of the main challenges to bringing existing flowing wells into compliance with the *WSA* and GPR are the costs to the well owner. Where the artesian head is low, flow may be controlled by adding an additional length of production casing, or in bedrock wells with competent surface seals, installing a packer or shale trap, as described above. However, in other cases where altering or equipping the well to control flow is not feasible, the well may have to be permanently decommissioned (also described above). Oftentimes this cost is unplanned. So, for private well owners, altering or equipping the well can pose an unexpected financial hurdle.

Cost will continue to be a significant barrier to compliance, particularly for private well owners who are often reluctant to spend the funds because they feel there is no direct benefit of controlling artesian flow.

7.2.2 Suggested Strategies for Promoting Compliance

The following strategies should help to promote compliance.

Information and Science

1) Continue to promote and enforce compliance of well record submission by the water well, geo-exchange and geotechnical drilling industries to increase information on flowing wells.
2) Continue to produce and update Flowing Artesian Advisories to alert practitioners and land owners about where flowing artesian conditions are known to occur.
3) Incorporate GIS maps from this study in the B.C. Water Resource Atlas and iMapBC so that they are publicly accessible for practitioners' use. The locations of existing flowing well advisories could also be shown. A user's guide would be helpful to explain the intended use of the maps, including:
    a. The limit of interpretation of the mapping results;
    b. The resolution of the maps given the scale at which they were done; and
    c. The preliminary nature of the maps to assess likelihood of encountering flowing artesian conditions during drilling.
4) Continue to support, as priority, groundwater science work to identify potential areas in other regions of flowing artesian conditions (e.g., map stratigraphy in major valleys with heavy groundwater use; analyze flow and geological conditions to gain understanding of where flowing artesian conditions will most likely occur).
5) Follow up with more detailed analysis in areas that were mapped as 'more likely than not' in this study. A detailed analysis could include, for example, geological modeling using a similar approach to that used in the case studies herein.

Policy

6) For flowing wells where the use of water requires a licence, consider including conditions in the licence to address stopping and controlling artesian flow. For existing non-domestic groundwater users, conditions may address how the well must be upgraded or replaced. For new non-domestic users, a licence could be dependent on a properly constructed well or, if a licence is issued prior to drilling the well, conditions can include directions on drilling the well to allow artesian flow to be stopped or controlled.
7) Consider designating specific areas/aquifers/conditions where a drilling authorization regulation can apply.

Financial Incentives

8) Consider providing access to matching funds from the provincial or local government to assist well owners in controlling or stopping flow in a Water Sustainability Plan area or where area-specific regulation exists where controlling artesian flow has been identified as a priority.

7.3 Review GPR Well Construction Standards

Since predicting where artesian flowing conditions will be encountered continues to be a challenge, the BCGWA has suggested that the province, with the help of the drilling industry, review and, where feasible, upgrade some of the siting and well construction standards in the GPR to incorporate best practices in regulation. An example is a greater length and thickness of surface seal. The minimum standards in the GPR can be reviewed from a "stopping and controlling artesian flow" perspective to identify the need for addition or upgrading of standards.

7.4 Area-Specific Advisories on Flowing Artesian Conditions

Three new well drilling advisories, and one modification to an existing advisory are recommended, based on the findings of this study. Importantly, these recommended advisories are based on detailed case studies selected from many areas where flowing artesian conditions are 'more likely than not'. However, there are other areas mapped as 'more likely than not' in each hydrogeologic context, and these other areas warrant more detailed examination.

7.4.1 New Bedrock Advisory for Naramata

Flowing bedrock wells in Naramata account for 13% of flowing bedrock wells in the Okanagan study area. As Figure 26 shows, flowing wells can occur immediately beside non-flowing wells of the same depth. Therefore, when drilling in fractured bedrock in this area there is an equal risk encountering flowing artesian conditions as not, even though the local area has been mapped a 'more likely than not'. A Well Drilling Advisory for Naramata would help to communicate this risk to drillers and landowners.

7.4.2 New General Bedrock Advisory for the Okanagan Basin

This study considered several factors that may influence occurrence of flowing conditions in bedrock in Okanagan Basin. While no single factor was a determining factor, the following factors were the most significant:

- Flowing wells seem to be located mostly in areas of topographic slope of ~10-15% (see Figure B2);
- Flowing wells seem to occur where the flow accumulation area (i.e., the uphill contributing area to a well) is thousands to hundreds of m^2 to ~0.5 km^2 in area (see Figure B4); and
- Flowing wells seem to occur in higher lineament (fracture and fault) density areas (see Figure B7 and Figure B8).

When these factors are present at a site, it suggests that fractures underneath the site may be connected to fractures that originate a distance uphill that have significantly higher head or pressure such that flowing conditions are likely to occur at the site (see Figure 26). Because these factors are present in many locations in the Okanagan, a general BEDROCK advisory for the Okanagan or alternatively, because these factors are likely present in other valleys in the province, general provincial level guidance on the risks of drilling in BEDROCK is recommended.

Messaging for drilling in BEDROCK should include the following elements:

- Information to help drillers and well owners become more aware of planning for encountering flowing artesian conditions WHEN DRILLING IN FRACTURED BEDROCK in areas such as the Okanagan Basin. Understanding factors affecting occurrence of flowing artesian conditions is based on the bedrock wells component of this project, which was entirely focused on the Okanagan Basin.
- The notes and cautions below could be conveyed on the provincial well drilling advisory webpage, and the MCA map for bedrock in the Okanagan shown.
- Guidance could also speak to how artesian flow, if encountered, can be stopped or controlled (i.e., proper installation of the production casing and surface seal, etc.).

Figure 14 shows areas where flowing artesian conditions are 'more likely than not' to occur in the Okanagan Basin based on the factors analyzed. Areas shown in red represent where these factors combine to result in a higher MCA score. That means, statistically, a well drilled in these areas is 'more likely than not' to encounter flowing conditions.

Note: Figure 14 is based on a statistical analysis; actual conditions can vary at any location and within a location, from well to well. This is because not all wells drilled within the same local area are drilled into the same fractures; this hit-and-miss nature of fractured bedrock should be communicated clearly to the well owner prior to drilling.

Caution: The map should never be over-interpreted; the map was generated at a large scale and should be used only as a preliminary tool to assess likelihood of encountering flowing conditions. It remains the driller's and well owner's responsibility to control artesian flow wherever it is encountered.

The maps are also most reliable at mid-elevation range within the Okanagan Basin because data are lacking in valley bottoms and at higher elevations (where bedrock lineaments data and bedrock wells are lacking).

7.4.3 New Advisory for Armstrong

Within the Okanagan, the majority of the flowing wells cluster within areas mapped as 'more likely than not' (see Figure 18). Advisories already exist for Westwold (Province of B.C., 2018a), Vernon Creek (Province of B.C., 2018c), Coldstream (Province of B.C., 2018b), and Lower Mission Creek area of Kelowna (Province of B.C., 2017b). Outside of these areas, Armstrong contains both bedrock and unconsolidated flowing wells, and has one of the highest rates of flowing well occurrence in the Okanagan.

Based on the mapping results, the area around Armstrong was mapped as 'more likely than not' and also has a high number of flowing wells. There are 11 flowing bedrock wells and 42 flowing wells in unconsolidated material. The flowing bedrock wells are mostly around the outer margins of the confined aquifers in the area. The majority of the unconsolidated flowing wells occur within the extent of the mapped confined aquifers, with the exception of four wells in the northern part of the study area that lie outside the extent of the mapped confined aquifers but still within areas mapped as 'more likely than not' (red cells).

Three-dimensional geological modelling using Leapfrog indicated a more expansive extent of the confining unit than suggested by the extent of the mapped confined aquifers (Aquifers 102, 348, 349. 356. 1150, 1153, 1154, 1155, 1156). In particular, the modelled confining unit was shown to extend to the unconsolidated flowing wells north of Aquifer 102. Notwithstanding the uncertainties associated with geological modelling in Leapfrog, the modelling results suggest that there may be an additional confined aquifer (area identified with red arrows in Figure 29) or that the extent of one of the known confined aquifers (most likely Aquifer 102) needs to be extended. A Well Drilling Advisory is recommended for the Armstrong area.

7.4.4 Modification of Existing Advisory for Vernon Creek

An advisory exists for Vernon Creek (Province of B.C., 2018c). However, the case study for Vernon Creek suggests that topography also appears to control the occurrence of flowing wells in the area. This advisory could be modified to provide alert drillers and home owners that confining units are not necessary for flowing conditions. The advisory could also include the MCA results for Vernon Creek to show the aerial extent of high risk areas.

7.4.5 Modification of Existing Advisory for Aquifer 58 and a new Advisory for Aquifer 33

Within the Fraser Valley, the occurrence of flowing artesian wells in unconsolidated materials largely correlate with the mapping results, specifically in the Nicomekl-Serpentine valley (see Figure 22). This area was selected for a detailed examination of Aquifers 58 and 33. A Well Drilling Advisory already exists for the Nicomekl-Serpentine aquifer (Aquifer 58) in Surrey and Langley (Province of B.C., 2018d).

Flowing artesian wells are also known to exist in Aquifer 33 (the West of Aldergrove Aquifer). The Province shows 97 flowing wells correlated to Aquifer 33 (Province of B.C., 2021b), and 30 flowing wells that are within the extent of the aquifer but are not correlated to it. This inter-till aquifer is confined and comprised of sand and gravel aquifer. Two permeable units slope westward and merge into a single unit in the west (Province of B.C., 2020a).

Three-dimensional geological modelling using Leapfrog conducted in this study shows the glacial layer (assumed to be till) and clay layer extending throughout the model (see Figure 32). The confining lithologies (described as "clay" and "glacial" in the well records) dip westward towards Aquifer 58. The flowing artesian wells are located along the base of a ridge within the boundary of Aquifer 33 (Figure 32). A Well Drilling Advisory for Aquifer 33 is recommended, but perhaps only highlighting the western portion of the aquifer where a change in topography results in flowing artesian conditions. The MCA map for this area could be included in the advisory and a discussion added about the role of topographic controls on flowing wells to emphasize that confining conditions are not necessary for artesian flow.

In addition, the Well Drilling Advisory for Surrey and Langley (Aquifer 58) could be altered to exclude the highlands between the two river valleys.

8. CONCLUSIONS

8.1 Overview of Key Findings

The purpose of this research was to determine the likely areas and extent of flowing artesian conditions in the Okanagan Basin and Fraser Valley and explore physical factors that might influence flowing artesian occurrence. These study areas are some of the most densely populated areas in the province and have some of the largest proportions of flowing wells relative to non-flowing wells. Flowing (artesian) wells have the potential to be costly to stop or control especially when the possibility of encountering flowing artesian conditions is not known ahead of time. Additionally, when left to flow uncontrolled, flowing wells can contribute to water security concerns such as groundwater depletion.

The occurrence of flowing artesian conditions was mapped using available well data from GWELLS. As of June 2020, there were 8004 reported wells in the Okanagan Basin, 533 of which were reported to be flowing wells. Both flowing and non-flowing wells have higher occurrences in the valley bottoms. Non-flowing wells are relatively evenly distributed throughout the valley, while flowing wells are more heavily clustered in the central and northern Okanagan Basin. Flowing wells tend to occur wherever non-flowing wells occur, with few exceptions, most notably in the southern Okanagan (between Osoyoos and Oliver) where flowing wells occur sparsely despite the high occurrence of non-flowing wells. Aquifers in this area are unconfined and their water levels are likely controlled by Okanagan River. While the flowing wells are concentrated in the Okanagan valley, there are occurrences of flowing wells at higher elevation. Reported flow rates range up to 600 US gallons per minute (gpm), although these rates have not been field verified. Approximately, 43% of wells reported to be flowing, have no reported flow rates. Approximately 23.5% of flowing wells are drilled in bedrock, 66.8% are screened in unconsolidated sediments, and the remaining 9.8% are drilled in an unknown lithology. Due to this distribution of aquifer material type, flowing wells in the Okanagan Basin were separated into two hydrogeologic contexts for this study, bedrock and unconsolidated.

As of June 2020, there were 16,691 wells reported in the Fraser Valley, of which 786 were reported to be flowing wells. Non-flowing wells occur extensively throughout the study area and very few locations do not have wells drilled. Flowing wells occur sporadically throughout the Fraser Valley, but the majority are clustered in the low-lying areas within the Township of Langley and Surrey (immediately west of the

Township of Langley). The majority of these clustered wells were determined by Carmichael (2011) to occur in Aquifer 58, the Nicomekl-Serpentine Aquifer; however, some of the clustered wells occur outside of the Aquifer 58 boundary. The reported flow rates range up to 1800 USgpm, although approximately 43% of wells reported to be flowing have no reported flow rate. Flow rates between 1–10 USgpm are the most frequently reported values. Only 1% of the wells are drilled into bedrock, 83% are screened in unconsolidated sediments, and the remaining 16% are drilled in an unknown lithology. Due to the very low number of flowing wells completed into bedrock, flowing wells are only examined in the Fraser Valley for an unconsolidated context.

Multi-criteria analysis (MCA) was used to map the likelihood of flowing artesian conditions in three hydrogeological contexts: Okanagan bedrock, Okanagan unconsolidated and Fraser Valley unconsolidated. The following factors were considered as potentially influencing the occurrence of flowing artesian conditions: elevation, slope, topographic curvature, flow accumulation (uphill contributing area), topographic wetness index (TWI), mapped lineaments associated with different sets of regional fault and fracture zones (Okanagan bedrock only), soil drainage, soil texture, presence of confining unit, and stream proximity. The novel Analytical Hierarchy Process (AHP) approach compared the values of factors from where flowing wells occur to the values of factors where non-flowing wells occur, allowing for locations with distinct criteria that influence flowing well occurrence to take priority in the AHP.

Across the three hydrogeologic contexts, no single factor stood out as being the most influential for flowing wells to occur. Slope had the highest weight in each context and it is likely one of the most important factors, with lower slopes having the highest occurrence of flowing wells in the unconsolidated contexts and moderate slopes having the highest occurrence of flowing wells in the Okanagan bedrock context. However, even though slope was the highest weighted factor in the Fraser Valley unconsolidated and Okanagan bedrock contexts, the distinction between flowing and non-flowing wells was not significant enough to draw conclusions on flowing well occurrence without considering other factors. This highlights the importance of considering multiple factors.

In the Okanagan bedrock context, there was a distinct difference in factors determined to be significant relative to the unconsolidated contexts. Flow accumulation was among the most important factors for the Okanagan bedrock as were the lineament kernel densities, while elevation was not weighted highly. In the unconsolidated contexts, all of the terrain factors (apart from flow accumulation which was excluded) were highly weighted, and the majority of the factors found to be significant initially were generally evenly weighted. This can likely be attributed to the clustering of the flowing wells and the larger datasets for the unconsolidated contexts. In the Okanagan unconsolidated context, elevation, slope, TWI, soil drainage and presence of a confining unit were all weighted equally. In the Fraser Valley unconsolidated, elevation, slope, TWI, stream proximity, soil drainage, and presence of a confining unit were all weighted equally.

The multi-criteria analysis (MCA) maps visually appear to accurately map flowing artesian conditions better when flowing wells are clustered and when there are more data points. Accordingly, the Okanagan unconsolidated context appears to give the best mapping results for flowing artesian conditions. However, all of the maps have areas where flowing artesian conditions are ‘more likely than not’ that do not have any (or few) known flowing wells. The absence of flowing wells in these areas does not necessarily indicate that the maps are incorrect, as flowing wells may just not have been drilled there yet. In the southern Okanagan valley and in the Chilliwack area, the lack of flowing wells may also be because some of the aquifers in these areas are unconfined and fluvial in origin and the groundwater level is largely controlled by local river level. In the southern Okanagan, groundwater levels may be influenced by the dry climate. In the Chilliwack area, land reclamation and the associated drainage of

Sumas Lake in 1925 may have altered the natural hydrogeological conditions such that flowing wells do not occur.

The Okanagan bedrock context had the lowest achieved Wilcoxon Test significance level, and therefore, the standardized MCA score distribution was the closest between the flowing and non-flowing wells. Based on the visual assessment that flowing and non-flowing bedrock wells occur frequently in close proximity to each other throughout the Okanagan Basin, these results are expected. These results can be attributed to the similar occurrence of flowing and non-flowing bedrock wells, which suggests that mapping distinct regions where only flowing bedrock wells occur is more difficult. Therefore, it is likely that flowing artesian conditions can be encountered anywhere that non-flowing bedrock wells can be found in the Okanagan Basin. But the Okanagan bedrock context also had the smallest datasets available for both flowing and non-flowing wells which could also contribute to these results. The factors used for the Okanagan bedrock (particularly the terrain factors) may not be the best suited for assessing fracture fluid flow in order to map flowing artesian conditions. Fracture fluid flow and the relationship with flowing artesian conditions was explored further using the Naramata area as a case study.

The Okanagan unconsolidated had the highest degree of clustering of flowing wells in areas mapped as 'more likely than not'. This clustering is not seen in the distribution of non-flowing wells, which are more evenly distributed across the entire Okanagan Valley. Flowing wells do occur sporadically in the Okanagan but tend to occur in clusters in areas mapped as 'more likely than not'. This could lead to a false assurance that flowing wells will not occur outside of these areas.

Relative to the Okanagan contexts, the Fraser Valley had larger areas mapped as 'more likely than not' where few flowing wells occur. Areas with flowing artesian conditions could be present in these areas, but due to the presence of a productive unconfined aquifer few wells are drilled into deeper confined aquifer. The methodology also led to areas that were mapped as 'more likely than not' when they are likely not. This is because locations that share similar criteria with locations with high flowing well occurrence are also mapped as high flowing well occurrence, but they may be missing one determining factor. Maps that potentially overestimate the likelihood are more desirable than maps that underestimate the occurrence of flowing artesian conditions because they provide a conservative basis for decision making.

The statistical validation method indicated that the MCA maps accurately determined the extent of flowing artesian conditions in each hydrogeologic context. All maps produced in the MCA analysis met the statistical threshold set (a minimum Wilcoxon Test significance level of 15%). The main take away from the MCA maps and the percent frequencies graphs is that there are areas mapped as 'more likely than not' for encountering flowing artesian conditions, but flowing wells can occur across the entire study area for each hydrogeologic context. It is important to note that these maps do not indicate any locations where it is impossible for flowing wells to occur or any locations where flowing wells are guaranteed to occur, only where they are 'more likely than not' to occur.

Site specific case studies of flowing artesian conditions were carried out in Naramata (bedrock context), and South Vernon, Armstrong, and Aquifers 58 and 33 in Langley (unconsolidated contexts). These case studies indicate that the MCA maps are able to accurately determine the extent of the likelihood of flowing artesian conditions at local scales. The Naramata case study presented a vertical 2D conceptual model demonstrating how flowing and non-flowing bedrock wells can occur immediately adjacent to each other, which is consistent with the more stippled appearance of the Okanagan bedrock MCA map. In Vernon Creek, the MCA maps provided a reasonable extent to accompany the Well Drilling Advisory in the area. In Armstrong, the MCA maps highlighted an area mapped as 'more likely than not' that corresponds to a large number of flowing wells. A Well Drilling Advisory is recommended for this area. Finally, in Langley, the MCA results better refined where flowing artesian conditions could be encountered in Aquifer 58. Lastly, the MCA maps accounted for flowing wells that occur more sporadically outside of confining units. These wells may represent locations where the topography-controlled model is more influential.

8.2 Limitations

While the statistical results suggest that the MCA accurately predicts where flowing artesian wells are likely to occur in each hydrogeological context, there are several limitations of this study.

The first limitation is the source of data on flowing and non-flowing wells in GWELLS. While GWELLS is a well-populated database, one main limitation is that the reported flow rate is from the time of drilling, which may not reflect current/modern flow rates. Additionally, many of the flow rates are not reported, but have been assigned a small flow rate (0.01 gpm) to simply identify the wells as flowing (although this did not impact this study as flow rates were not used). GWELLS also does not include all wells in the province, only those that were historically reported voluntarily by drillers.

The second limitation is the scale used to map the flowing artesian conditions. The two study areas (Okanagan and Fraser Valley) are large regional study areas with complex groundwater flow systems and flow paths that have not been adequately characterized. Each flow system likely has independent relationships between the factors and flowing well occurrence. For example, flowing wells are generally 'more likely than not' to occur at low elevations along the groundwater flow path, but the elevation at which a potentiometric surface transitions from below ground surface to above ground surface is variable for each groundwater flow system. Moreover, currently it is not possible to undertake a site level study using provincial well data, because 1) the data have been accumulated over decades, 2) the artesian pressures and flows were generally not measured or were only estimated, and 3) fracture networks are not characterized at the site scale. Therefore, a regional scale for mapping was taken in this study as a starting point for more focused studies. The advantage of conducting the mapping on a regional scale is the larger dataset available for use, which allows broad relationships to be identified.

A third limitation is the availability of data. In the Fraser Valley unconsolidated context the number of wells able to be used for the analysis was extensive and covered the entire study area. The two hydrogeologic contexts in the Okanagan (bedrock and unconsolidated) have a lower well density, and the wells (flowing and non-flowing) tend to occur predominantly in the valley bottoms. Because there are fewer wells drilled outside of the valley bottom in the Okanagan, it is hard to say whether these areas were assigned low likelihood scores because there are simply no wells occurring there or because there are actually no flowing artesian conditions. The Okanagan bedrock context has the smallest dataset, as well as has having a slightly lower achieved significance level in one of the Wilcoxon Tests.

Lastly, these maps were largely driven by surficial and terrain factors. While the data required to process these factors are readily available in most regions and the factors themselves are widely applicable, they may be limited in their ability to capture the intricacies of complex groundwater flow systems. Elevation, slope, curvature, flow accumulation and topographic wetness index are all derived directly from a DEM, and while stream proximity is also a surficial indicator it is not DEM derived. Lineament density gives a representation of subsurface groundwater flow but was only applicable to one hydrogeology context (Okanagan bedrock). Soil drainage is technically a surficial factor, but components that contribute to drainage, like soil texture, can effectively have confining properties and have a more direct link to the subsurface groundwater characteristics. The map results may become more accurate by incorporating more subsurface factors that can represent the complex groundwater flow systems, but these factors are difficult (cost, scale) to characterize.

8.3 Recommendations for Well Drilling Advisories

Throughout the Fraser Valley and Okanagan Basin there is potential for developing additional Well Drilling Advisories or revising existing ones. Specifically, the regions of Naramata and Armstrong would benefit from new advisories, and the existing advisory for Aquifer 58 could be modified.

In the Okanagan, the occurrence of flowing wells is highly variable. This high variability, demonstrated through the MCA map and the case study in Naramata, could lead to a sense of false sense of security that flowing artesian conditions will not be encountered. For this reason, we recommend a region-wide advisory for drilling in bedrock in the Okanagan. Alternatively, the Province could provide general guidance on the risks of drilling in bedrock. The elements of a potential advisory are provided in Section 7.4.1. The MCA map could be included in the general advisory and made available to drillers as a .kml file so that it can be viewed in Google Maps.

Armstrong contains both bedrock and unconsolidated flowing wells and has one of the highest rates of flowing well occurrence, excluding areas with existing Well Drilling Advisories in the Okanagan. Both the MCA maps and the case study in Armstrong, point to a need for an advisory in this area (see Section 7.4.2).

In the Fraser Valley, a new advisory is recommended for Aquifer 33, but perhaps only highlighting the western portion of the aquifer where there is a change in topography results in flowing artesian conditions. The existing advisory for Surrey and Langley (Aquifer 58) could be modified to exclude the highlands between the Nicomekl and Serpentine valleys. This advisory could also potentially be modified to include Aquifer 33 as the flowing wells are in the immediate vicinity (see Section 7.4.3).

Well Drilling Advisories do not need to be limited to those recommended in this study. This study focused on only four areas that were mapped as 'more likely than not'. However, areas mapped as 'more likely than not' occur in other areas, which warrant more detailed examination.

8.4 Potential Uses of the Likelihood Maps

The maps developed in this study were used to identify areas that are statistically more likely to have a higher occurrence of flowing wells. The maps were then used to investigate specific areas where flowing wells were mapped as 'more likely than not' to occur and to recommend Well Drilling Advisories as appropriate in those areas, but there are several other potential uses for the maps, notably providing a tool for well drillers to use in their decision making surrounding well drilling, in discussions with land owners about risks, but also potentially for drilling authorizations. The methods used in this study can also be extended to other areas of the province.

8.4.1 Guidance for Well Drillers

The Well Drilling Advisories are a good resource for site specific inquiries, but this research showed that a large portion of flowing wells occur outside the current and recommended Well Drilling Advisories. The MCA maps produced in this research provide information on a regional scale for drillers. Drillers can use the MCA maps (in conjunction with known flowing (and non-flowing) well locations to inform their decision around drilling and preparation. Drillers can identify the potential drilling site on the map (maps will be provided as a .kml file for use in applications such as Google Earth), identify if the area is mapped as 'more likely than not' (or is adjacent to an area mapped as 'more likely than not'), and whether there are flowing wells and non-flowing wells in the area. They can use this information and their professional judgement to assess the likelihood of flowing artesian conditions. Importantly, the maps should not be relied upon as the sole information source due to various limitations (see Section 8.2). The maps are simply meant to aid in the decision-making process.

The percent frequency graphs in Appendix B could also be used as guidance for drillers on the potential occurrence of artesian conditions at locations outside of the case study areas. Flowing wells occur across a range of values for each factor and the specific values will be relative to the specific site, but the general trends can be evaluated. For example, flowing wells tend to occur at lower elevation and lower slopes in unconsolidated material, but what value is considered 'low elevation' is site specific. Other factors, such as stream proximity and soil drainage, are more likely to be consistent across site locations.

8.4.2 Drilling Authorizations and Conditions of the Statutory Decision Maker

Under *the WSA*, new wells that are drilled for non-domestic use require an authorization. Authorizations and associated requirements under the *WSA* are administered by FLNRORD. In areas where the water supply, the environment, property, or public safety require additional protection from well construction and testing activities, the Province of B.C. has authority to enact a regulation under the *WSA* to require a drilling authorization to require permits for these activities. The maps produced in this study could be used to help inform drilling authorization decisions in the Okanagan Basin and Fraser Valley.

In cases where an authorization is granted prior to the well being drilled, the statutory decision maker can use the maps to inform any conditions for drilling the well to ensure any artesian flow that is encountered can be stopped or controlled.

8.4.3 Future Mapping

The methods developed for mapping the likelihood of encountering flowing wells can be applied to other regions were flowing wells are known to occur. This may require adapting the methodology for cases where one or more datasets are not available; for example, the lineament datasets used in the bedrock context. The methodology can be adapted to accommodate the factors available for other areas, although the ranges for each factor may need to be adjusted to account for the specific conditions in other regions. This methodology was developed as a regional mapping method, and so it relies on some coherency in groundwater flow patterns across the study region. In this thesis, the two study areas were a regional basin and a valley bottom, both of which are representative of regional groundwater flow systems. Thus, attention should be paid to the spatial scales of the datasets if this methodology is applied to other locations.

8.4.4 Decision Support Tools

This study also delved into the issue of complying with *WSA* s. 52 and s. 53 in stopping and controlling artesian flow. Technically, methods are available to stop or control artesian flow when drilling a new well or dealing with flow from an existing well. The cost will depend on the type of aquifer, local geology, artesian head and flow, and design, construction and state of a well, among other things. The two main barriers to compliance are: significant (and unexpected) cost and confusion about liability of the practitioner under WSA s. 52 (3), 52 (5) and 53 (1).

The following strategies/suggestions should help promote compliance:

1) Continue to promote and enforce compliance of well record submission to increase information on flowing wells.
2) Continue to produce Flowing Artesian Advisories to alert practitioners and land owners about where flowing artesian conditions are known to occur.
3) Incorporate the GIS maps from this study in the BC Water Resource Atlas and iMapBC so that they are publicly accessible. A user's guide would be helpful to explain the intended use of the maps.

4) Continue to identify and characterize potential areas in other regions of flowing artesian conditions.
5) Follow up with more detailed analysis in areas that were mapped as 'more likely than not' in this study.
6) Explore developing a risk matrix to guide staff in responding to complaints of non-compliance and in assessing options on how best to bring a flowing well into compliance.
7) For flowing wells where the use of water requires a licence, consider including conditions in the licence to address stopping and controlling artesian flow.
8) Consider designating specific areas/aquifers/conditions where a drilling authorization regulation can apply.

Finally, with the help of the drilling industry, the minimum standards in the GPR can be reviewed from a "stopping and controlling artesian flow" perspective to identify the need for addition or upgrading of standards in the regulation.

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APPENDIX A: DETAILED WORKFLOW FOR MULTI-CRITERIA ANALYSIS

Figure A1 displays the workflow for data processing. The blue diamonds represent unprocessed spatial data (i.e., data files from Table 3) that were used to derive the factors evaluated for the multi-criteria analysis (MCA). The beige hexagons represent the geoprocessing tools in ArcMap that were used to produce the factors from the original unprocessed spatial data. The purple rhomboids represent the final factors produced after they have undergone the GIS processing. Overlapping rhomboids indicate when multiple factors were produced (e.g., multiple lineaments sets). The green hexagons represent the non-GIS processing tool (i.e., Matlab) used to conduct the Wilcoxon Rank Sum Test. This test was used to determine the significance of each factor and is detailed in Section 4.5. The black arrows are used to represent the flow between data processing and factors. The following subsections describe the data processing for each factor in more detail.

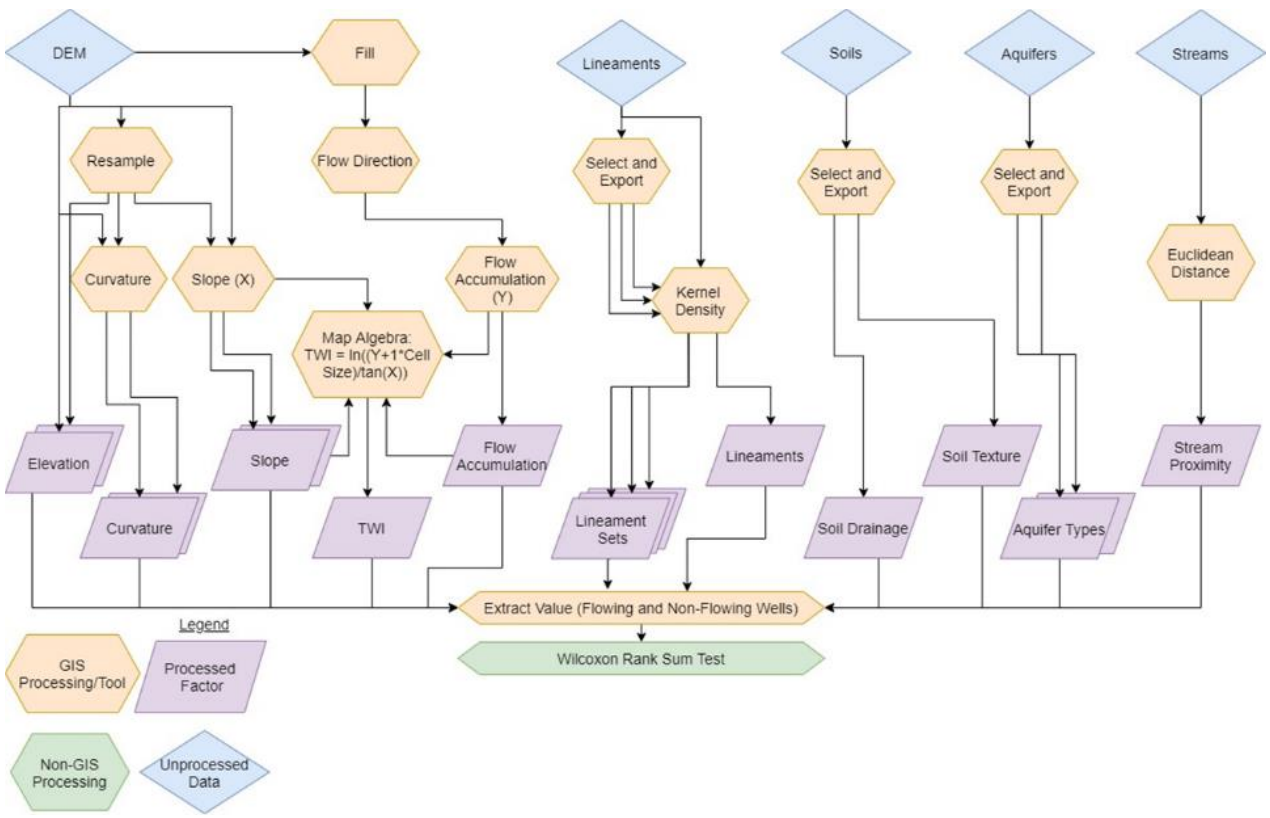

Figure A1: Workflow for data processing all factors.

A1. DEM and DEM-Derived Factors

The DEM was sourced from DataBC (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2012) and has a cell size of 20.5 m x 20.5 m. Elevation, slope and curvature were computed in ArcMap using the GIS Tools of the same names (Figure A1). Curvature is sensitive to the cell size of the raster and was examined at both the original grid size (20.5 m x 20.5 m) as well as double the grid size (41 m x 41 m). Elevation and slope were also examined at both resolutions for consistency. These DEM manipulations were processed using the 'Resample' tool.

The final factor maps for elevation (Figure B1) and slope (Figure B2) used the original grid size, while curvature (Figure B3) used the larger grid size. The larger grid size was found to have values within more acceptable ranges; curvature values for steep terrain generally range from - 4 (convex) to + 4 (concave). The legend for Figure B3 indicates the raster for the Okanagan bedrock has curvature values ranging from - 10 to + 8.5. This is deemed acceptable because the majority of the map's curvature values fall within the acceptable range of - 4 to + 4.

Flow accumulation is calculated using the flow accumulation tool in ArcMap through a series of steps. To calculate flow accumulation, the 'Fill' tool in ArcMap is applied to the DEM to remove sinks and peaks that could be due to potential errors from the DEM resolution. Sinks and peaks are cells with elevations that are lower or higher than would be expected based off the surrounding cells. The ArcMap manual recommends using the 'Fill' tool before delineating contribution areas. The filled DEM is then used to calculate a flow direction raster. Flow direction is calculated from the filled DEM using the GIS tool of the same name. The flow direction output indicates the direction of flow out of each cell based on the steepness of the surrounding cells. The 'Flow Accumulation' tool is then applied to the flow direction raster to produce of map of flow accumulation (Figure B4).

ArcMap does not have a GIS tool to compute TWI, although several algorithms have been developed to calculate TWI, and many GIS software packages have built-in tools for the calculation (Mattivi et al., 2019; Kopecky et al., 2021). In this study, the 'Raster Calculator' tool was used to compute TWI using Equation A1 (Beven and Kirby, 1979).

$$TWI = \ln\left(\frac{Y * Cell\ Size}{tan\left(X * \left(\frac{\pi}{180}\right)\right)}\right) \tag{A1}$$

where:

Y = flow accumulation

X = slope

Cell size = 20.5 m.

A2. Lineaments

Lineaments in the Okanagan are considered to be associated with three sub-vertical fracture sets (Table A1; Voeckler and Allen, 2012). Figure B6 shows the mapped lineaments in the Okanagan for all sets combined. A kernel density map of the lineaments was produced in ArcMap (Figure B7), following a similar approach by Voeckler and Allen (2012). The 'Kernel Density' tool in ArcMap uses a kernel function to fit a smooth, rounded surface over each polyline and the surface tapers radially outwards. The densities are calculated based on the overlapping surfaces of the lineaments. The density values were extracted at both flowing and non-flowing wells. Wells that fell outside the mapped lineament density area were excluded from analyses (39 wells excluded).

Figure B8 shows the lineaments separated by fracture set. Two fracture sets from Voeckler and Allen (2012) were grouped together as a single set because differences in dip direction cannot be accounted for in a two-dimensional GIS environment. The same kernel density analysis was conducted on each strike lineament set (set 1 in Figure B9, set 2 in Figure B10, set 3 in Figure B11).

Table A1: Lineament sets used in this study and the original lineament sets from Voeckler and Allen (2012).

Lineament Set	Voeckler and Allen Set	Strike Range (°)
Set 1	Set 1 & Set 2	0-50
Set 2	Set 3	> 50-113
Set 3	Set 4	> 113-180

A3. Soils

Soil texture polygons (Figure B12) and soil drainage polygons (Figure B13) were obtained from the BC Soil Information Finder Tool (SIFT) (B.C. Ministry of Environment and Climate Change Strategy, 2018b). SIFT provides access to soil survey mapping and soil attributes and provides consistent coverage throughout the study areas. In the SIFT database, texture is classified by the percentage of sand and clay in the soil (Figure A2) and drainage as described in Table A2. Each soil polygon allows for up to three classes of the texture and drainage for each polygon to account for potential spatial variations. For simplicity, and because the spatial variation was unknown, the attribute with the highest percentage was applied to the entire polygon. In ArcMap the number of wells which occurred in each polygon was determined using the 'select' tool.

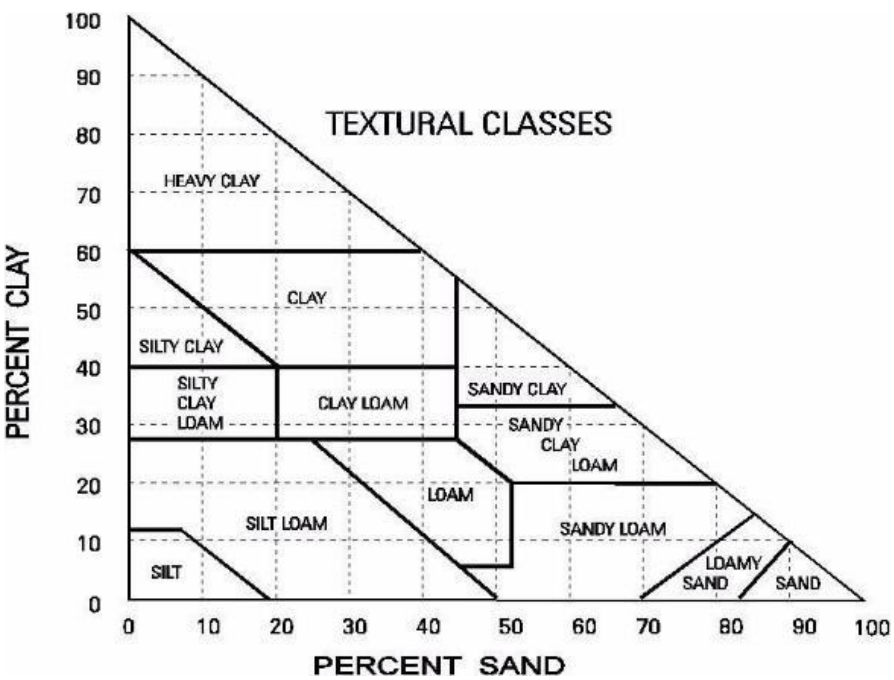

Figure A2: Soil textural classes used in the SIFT databased to classify soil types based on the percent of sand and clay in samples. Sourced from http://sis.agr.gc.ca/cansis/glossary/t/.

Table A2: Soil drainage classifications (B.C. Ministry of Community, Sport and Cultural Development n.d.).

Drainage	Description
Very Rapidly Drained (VP)	The soil moisture content seldom exceeds field capacity in any horizon except immediately after water additions. Water is removed from the soil very rapidly in relations to supply. Excess water flows downward very rapidly if underlying material is pervious. There may be very rapid subsurface flow during heavy rainfall provided there is a steep gradient. Soils have very limited water storage capacity (usually less than 2.5 cm) within the control section and are usually coarse textured, or shallow, or both. Water source is precipitation.
Rapidly Drained (R)	The soil moisture content seldom exceeds field capacity in any horizon except immediately after water additions. Soils are free from any evidence of gleying or mottling throughout the profile. Rapidly drained soils often occur on steep slopes.
Well Drained (W)	The soil moisture content seldom exceeds field capacity in any horizon (except possibly the C) for a significant period of the year. Soils are usually free from mottling in the upper 1 m but may be mottled below this depth.
Moderately Well Drained (MW)	The soil moisture remains in excess of field capacity for a small but significant period of the year. Soils are often mottled in the lower B and C horizons or below a depth of 0.7 m. The Ae horizon, if present, may be faintly mottled in fine textured soils and in medium textured soils that have a slowly permeable layer below the A and B horizons. In grasslands soils the B and C horizons may be only faintly mottled and the A horizon may be relatively thick and dark.
Imperfectly Drained (I)	The soil moisture remains in excess of field capacity in subsurface horizons for moderately long periods during the year, soils are often distinctly mottled in the B and C horizons; the Ae horizon, if present, may be mottled. The matrix generally has a lower chroma than in the well drained soil on a similar parent material, Soils are generally “gleyed” subgroups of mineral soil orders
Poorly Drained (P)	The soul moisture remains in excess of field capacity in all horizons for a large part of the year. The soils are usually strongly gleyed, except in high chroma parent materials, the B, if present, and upper C horizons usually have matrix chroma of three or fewer, prominent mottling may occur throughout. Soils are generally in the Gleysolic or Organic order.
Very Poorly Drained (VP)	Free water remains at or within 30 cm of the surface most of the year. The soils are usually strongly gleyed. Subsurface horizons usually are of low chroma and yellowish to bluish hues. Mottling may be present within 30 cm or at depths in the profile. Soils are generally in the Gleysolic or Organic order; mineral soils are usually peaty phase.

A4. Presence of Confining Unit

A detailed examination of well lithology logs is typically carried out to identify the presence of a confining unit, but due to the complexity of the subsurface sediments and the large number of wells in each area, this study relied on aquifer polygons. Aquifer polygons were obtained from DataBC as the ‘Ground Water Aquifers’ spatial coverage (B.C. Ministry of Environment and Climate Change Strategy, 2018a). This data set classifies the aquifer type and includes descriptors indicating whether aquifers are confined or unconfined. A complicating issue for this analysis is that wells are not consistently assigned to specific aquifers. Additionally, the aquifers do not have well defined depths spatially - only approximate depths across the entire aquifer are reported.

Therefore, after some experimentation with methods to separate the wells by aquifer, any wells that occur in a confined polygon were considered confined and any wells that occur outside of a confined polygon were considered unconfined. The ‘Select’ tool in ArcMap was used to select flowing wells within the confined aquifer polygon (regardless of overlap with unconfined polygons). The ‘Select’ tool in

ArcMap was then used to select flowing wells that did not occur in the confined polygons. This process was repeated for non-flowing wells. This method eliminated having wells counted as both confined and unconfined. However, the method considers some unconfined wells to be in confined aquifers where the polygons overlap.

A5. Stream Proximity

Stream locations were obtained through DataBC as the ‘Freshwater Atlas Stream Network’ spatial coverage (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2011). A raster with the proximity to a stream at every cell was created using the ‘Euclidean Distance’ tool. Then the distance from the wells to the stream were extracted at the well locations. The Euclidean Distance tool produces values that represent the linear map distance between the well and the closest point of a stream and does not account for inclination in topography in the distance calculation. Stream proximity was evaluated for all three hydrogeological contexts.

A6. Relative Importance of Factors and Their Weights

Factor weights were determined through a modification of Saaty’s (1987) Analytical Hierarchy Process (AHP), which is a pairwise comparison method. The method is used to rank factors against each other to determine which factors are most important / have the greatest influence. For example, Column 1 in Table A3 (Intensity of Importance) shows Saaty’s fundamental scale used to rank factors against each other, column 2 includes the explanation for how to rank the factors, and column 3 describes how the qualitative relationships are assessed.

Table A3: The Fundamental scale for intensity of importance, based on Saaty (1987) pairwise comparison method.

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i.*	A reasonable assumption

Rather than use Saaty's qualitative ranking, in this study the Wilcoxon Rank Sum test was conducted for each factor starting at the lowest acceptable significance level (15%). Then the test was repeated for increasing significance levels until the highest significance level was determined. For example, in Table A4 (for Okanagan bedrock) elevation was first tested at 15% significance level, and then retested at 10% and found to be significant. Elevation was then retested at a significance level of 5% and found not to be significant. In Table A4 the highest achieved significance level is represented by a green cell. A value of 1 indicates that the factor is significant at that significance level, and a 0 indicates that the factor is not significant at that level. Essentially, the Wilcoxon Test is testing the same hypotheses from Section 4.3, but at varying significance levels. Table A5 and Table A6 show the Wilcoxon Test results for the Okanagan unconsolidated and Fraser Valley unconsolidated, respectively.

Table A4: Okanagan bedrock significance levels as determined by the Wilcoxon Test for the final factors used to determine the weights for the MCA. Green cells indicate the highest significance level achieved for each factor. A value of 1 indicates where the null hypothesis is rejected; a value of 0 indicates failure to reject the null hypothesis.

	Wilcoxon Significance Level				
	0.10%	**1%**	**5%**	**10%**	**15%**
Elevation	0	0	0	1	1
Slope	1	1	1	1	1
Curvature (41m x 41m)	0	0	0	0	1
Flow Accumulation	1	1	1	1	1
Lineament Density 1	0	1	1	1	1
Lineament Density 2	0	0	1	1	1
Lineament Density 3	0	1	1	1	1

Table A5: Okanagan unconsolidated significance levels as determined by the Wilcoxon Test for the final factors used to determine the weights of the MCA. Green cells indicate the highest significance level achieved for each factor. A value of 1 indicates where rejection of the null hypothesis can be rejected. A value of 0 indicates failure to reject the null hypothesis.

	Wilcoxon Significance Level					
	0.001%	**0.10%**	**1%**	**5%**	**10%**	**15%**
Elevation	1	1	1	1	1	1
Slope	1	1	1	1	1	1
TWI	1	1	1	1	1	1
Flow Accumulation	0	1	1	1	1	1
Stream Proximity	0	0	0	0	0	1
Soil Drainage	1	1	1	1	1	1
Confining Unit	1	1	1	1	1	1

Table A6: Fraser Valley significance levels as determined by the Wilcoxon Test for the final factors used to determine the weights of the MCA. Green cells indicate the highest the significance level achieved for each factor. A value of 1 indicates where rejection of the null hypothesis can be rejected. A value of 0 indicates failure to reject the null hypothesis.

	Wilcoxon Significance Level					
	0.001%	**0.10%**	**1%**	**5%**	**10%**	**15%**
Elevation	1	1	1	1	1	1
Slope	1	1	1	1	1	1
TWI	1	1	1	1	1	1
Flow Accumulation	0	0	0	0	1	1
Stream Proximity	1	1	1	1	1	1
Soil Drainage	1	1	1	1	1	1
Confining Unit	1	1	1	1	1	1

The next step was to create the pairwise comparison matrix. The matrix for the Okanagan bedrock is displayed in Table A7, as the example. The pairwise comparison matrices for the Okanagan unconsolidated and Fraser Valley unconsolidated can be found in Table A7, Table A8 and Table A9, respectively. Using Table A7 as an example, the upper matrix indicates the relative importance between factors using Saaty's 'Intensity of Importance' scale. The individual factors are in the row headers and column headers, while the relative importance between each of the paired factors is indicated in the cells. The relative importance between two factors is read from the table as "'row factor y' is 'cell XY' as important as 'column factor x'". For example, slope (Row 3) is 7x as important as elevation, i.e., slope has a very strong importance relative to elevation. In the pairwise comparison matrix, each factor pair occurs twice because each factor occurs in both the row and the column. Because the table is read across the rows, the second time the pairs are compared, the reciprocal value of relative importance is assigned to the cell. For example, when slope and elevation are compared in Row 2, it is read as "elevation is 1/7x as important as slope".

Relative importance values from Table A7 were determined quantitatively by comparing the highest achieved Wilcoxon significance levels from Table A4. The differences in the highest achieved Wilcoxon significance levels were then associated with values from Saaty's (1987) intensity of importance scale. If two factors had the same highest achieved Wilcoxon significance level, a value of 1 was assigned to the cell, indicating that the two factors are of equal importance. For example, slope and flow accumulation have the same highest achieved significance level (0.10%; Table A4) and were assigned a value of 1 in Table A7. When two factors did not achieve the same highest significance level, the difference equated to an increase or decrease in relative importance. If there was a single level of difference (e.g., 0.10% vs 1%; 1% vs 5% etc.; Table A4), then a value of 3 (or 1/3) was assigned to the cell in Table A7. If there were two levels of separation (e.g., 0.10% vs 5%), then a relative importance value of 5 (or 1/5) was assigned the cell. For example, slope and lineament density set 1 have significance levels of 0.10% and 1%, respectively (Table A4), and have a relative importance value of 3 (and 1/3) assigned in Table A7.

Table A7: Okanagan bedrock pairwise comparison matrix for the Analytical Hierarchy process and the subsequent calculations used to determine the weight of each factor. The blue cells represent the column sum for the relative importance of each factor (Equation A2). The yellow cell indicates the example calculation from Equations A5 and A6. The purple cells indicate the row sum calculated using Equation A9. The green cells indicate the final weights calculated from Equation A9.

	Elevation	Slope	Curvature	Flow Acc.	Lin. Density 1	Lin. Density 2	Lin. Density 3		
Elevation	1	1/7	3	1/7	1/5	1/3	1/5		
Slope	7	1	9	1	3	5	3		
Curvature	1/3	1/9	1	1/9	1/7	1/5	1/7		
Flow Accumulation	7	1	9	1	3	5	3		
Lin. Density 1	5	1/3	7	1/3	1	3	1		
Lin. Density 2	3	1/5	5	1/5	1/3	1	1/3		
Lin. Density 3	5	1/3	7	1/3	1	3	1		
Column Sum	28.33	3.12	41.00	3.12	8.68	17.53	8.68		
								Row SUM	**Final Weight**
Elevation	0.07	0.05	0.07	0.05	0.02	0.02	0.02	0.30	0.04
Slope	0.24	0.32	0.22	0.32	0.35	0.29	0.35	2.08	0.30
Curvature	0.01	0.04	0.02	0.04	0.02	0.01	0.02	0.15	0.02
Flow Accumulation	0.24	0.32	0.22	0.32	0.35	0.29	0.35	2.08	0.30
Lin. Density 1	0.17	0.11	0.17	0.11	0.12	0.17	0.12	0.96	0.14
Lin. Density 2	0.10	0.06	0.12	0.06	0.04	0.06	0.04	0.49	0.07
Lin. Density 3	0.17	0.11	0.17	0.11	0.12	0.17	0.12	0.96	0.14

Table A8: Okanagan unconsolidated pairwise comparison matrix based on the Wilcoxon Test results and the calculated weights.

	Elevation	**Slope**	**TWI**	**Flow Accumulation**	**Stream Proximity**	**Soil Drainage**		
Elevation	1	1	1	3	9	1		
Slope	1	1	1	3	9	1		
TWI	1	1	1	3	9	1		
Flow Accumulation	1/3	1/3	1/3	1	7	1/3		
Stream Proximity	1/9	1/9	1/9	1/9	1	1/9		
Drainage	1	1	1	3	9	1		
Column Sum	4.44	4.44	4.44	13.11	44.00	4.44		
							Row SUM	**Final Weight**
Elevation	0.23	0.23	0.23	0.23	0.20	0.23	1.33	0.22
Slope	0.23	0.23	0.23	0.23	0.20	0.23	1.33	0.22
TWI	0.23	0.23	0.23	0.23	0.20	0.23	1.33	0.22
Flow Accumulation	0.08	0.08	0.08	0.08	0.16	0.08	0.54	0.09
Stream Proximity	0.03	0.03	0.03	0.01	0.02	0.03	0.13	0.02
drainage	0.23	0.23	0.23	0.23	0.20	0.23	1.33	0.22

Table A9: Fraser Valley pairwise comparison matrix based on the Wilcoxon Test results and the calculated weights.

	Elevation	Slope	TWI	Flow Accumulation	Stream Proximity	Soil Drainage	Confining Unit		
Elevation	1	1	1	9	1	1	1		
Slope	1	1	1	9	1	1	1		
TWI	1	1	1	9	1	1	1		
Flow Accumulation	1/9	1/9	1/9	1	1/9	1/9	1/9		
Stream Proximity	1	1	1	9	1	1	1		
Drainage	1	1	1	9	1	1	1		
Confining	1	1	1	9	1	1	1		
Column Sum	6.11	6.11	6.11	55.00	6.11	6.11	6.11		
								Row SUM	**Final Weight**
Elevation	0.16	0.16	0.16	0.16	0.16	0.16	0.16	1.15	0.16
Slope	0.16	0.16	0.16	0.16	0.16	0.16	0.16	1.15	0.16
TWI	0.16	0.16	0.16	0.16	0.16	0.16	0.16	1.15	0.16
Flow Accumulation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.13	0.02
Stream Proximity	0.16	0.16	0.16	0.16	0.16	0.16	0.16	1.15	0.16
Soil Drainage	0.16	0.16	0.16	0.16	0.16	0.16	0.16	1.15	0.16
Confining Unit	0.16	0.16	0.16	0.16	0.16	0.16	0.16	1.15	0.16

The final step was to calculate the weights for each factor from the pairwise comparison matrix (lower part of Table A7). The weight for each factor was calculated using Equations A2-A4. The weight calculation for the slope factor is provided as an example in each step.

The column sum for each factor was calculated using Equation A2 and is shown as the blue cells in Table A7.

$$\sum_{i=1}^{n} R.I._i = R.I._1 + R.I._2 + \cdots + R.I._n \qquad \text{(Eq. A2)}$$

where:

R.I. = Relative Importance; Grey/White cells in pairwise comparison matrix

$$\sum_{i=1}^{n} R.I._{Slope} = \frac{1}{7} + 1 + \frac{1}{9} + 1 + \frac{1}{3} + \frac{1}{5} + \frac{1}{3} = 3.12 \qquad \text{(Eq. A3)}$$

The relative importance value for each factor was then divided by the column sum, populating the lower portion of Table A7 to produce a normalised relative importance value (Equation A4). The normalised relative importance is shown as white cells in lower portion of Table A7.

$$N.R.I. = R.I_n \,/\, \sum R.I. \qquad \text{(Eq. A4)}$$

where:

N.R.I. = Normalised relative importance value.

The example calculation for the N.R.I. is provided for the cell that represents the slope x slope intersection and is highlighted in yellow in Table A7.

$$N.R.I.(slope\ x\ slope) = R.I._{slope\ x\ slope} / \sum R.I._{slope} \quad \text{(Eq. A5)}$$

$$N.R.I.(slope\ x\ slope) = \frac{1}{3.12} = 0.32 \quad \text{(Eq. A6)}$$

Then the Row Sum of the lower table is calculated for each factor and is shown as purple cells in Table A7 (Equation A7).

$$\sum N.R.I._{f} = N.R.I._{f1} + N.R.I._{f2} + \cdots + N.R.I._{fn} \quad \text{(Eq. A7)}$$

$$\sum N.R.I._{slope} = 0.24 + 0.32 + 0.22 + 0.32 + 0.35 + 0.29 + 0.35 = 2.08 \quad \text{(Eq. A8)}$$

The final step was to calculate the weight, by dividing the row sum for a factor by the row sum of all factors and is shown as green cells in Table A7 (Equation A9).

$$Final\ Weight = \sum N.R.I._{f} / \sum\left(\sum N.R.I._{f}\right) \quad \text{(Eq. A9)}$$

$$Slope\ Weight = \frac{2.08}{(0.30+2.08+0.15+2.08+0.96+0.49+0.96)} = 0.30 \quad \text{(Eq. A10)}$$

Table 5 in the main body of the report shows the final weights for each factor.

A7. Factor Standardization

The percent frequency of flowing wells occurring in the bin intervals for each factor was first calculated (Equation A11). Binned ranges from the original scale were converted to the new dimensionless scale based on the percent frequency of flowing wells occurring in each bin interval (Equations A12-A13). The new standardized scale therefore conveys the occurrence frequency of flowing wells. After the percent frequencies were determined, the standardization constant was calculated using Equation A12. A single Standardization Constant is needed for each factor. The Standardization Constant is calculated from the maximum standardized score that is desired for the factor. For this study a maximum standardized score of 100 was used for all factors. The standardization constant and the percent frequency were then multiplied (Equation A13) to calculate the new standardized score for that bin interval. In order to include categorical data (i.e., soil drainage and aquifer type) these data sets had a numerical value assigned to each category to create a scale for standardization.

$$\%\ Frequency = \frac{\#\ wells\ in\ BIN}{Total\ Wells} \quad \text{(Eq. A11)}$$

$$Standardization\ Constant = \frac{Maximum\ Standardization\ Score}{Highest\ \%\ Frequency\ Value} \quad \text{(Eq. A12)}$$

$$Standardized\ Score = \%\ Frequency * Standardization\ Constant \quad \text{(Eq. A13)}$$

An example of the standardized scores for elevation in the Okanagan bedrock is provided in Table A10. Sample calculations are shown in Equation A14-A15. Table A10 shows how bin intervals with a higher percent frequency were assigned a higher value in the standardized scale. The bin intervals with the highest frequency of flowing wells were always assigned a standardized score of 100. This method also results in bin intervals with no occurrence of flowing wells being assigned a standardized score of 0.

$$\%\ Frequency\ of\ elevations > 200 - 400\ masl = \frac{5}{94} = 5.3\ \% \quad \text{(Eq. A14)}$$

$$Standardization\ Constant = \frac{100}{35.1\%} = 2.84 \quad \text{(Eq. A15)}$$

$$Standardized\ Score = 5.3 * 2.84 = 15.2 \quad \text{(Eq. A16)}$$

Table A10: Standardized scores for the elevation factor in the Okanagan bedrock.

Elevation			
Bin (masl)	**Frequency**	**% Frequency**	**Standardized Score**
>0 -200*	n/a	n/a	n/a
>200-400	5	5.3	15.2
>400-600	33	35.1	100.0
>600-800	27	28.7	81.8
>800-1000	19	20.2	57.6
>1000	6	6.4	18.2
Standardization Constant	2.84		

*Elevations lower than 200 masl do not occur in the Okanagan study area

The standardized scores for each hydrogeological context can be found in Table A11 – Table A13. Each factor's scale was converted to the standardized scale using the 'Reclassify' tool in ArcMap. These scores, coupled with the weights determined above (Tables A7-A9), were used in the weighted linear equation (Section 4.7) to create the final MCA maps.

Table A11: Okanagan bedrock bin intervals and the standardized raster scores.*

Elevation (masl)	Standardized Score
200	n/a
400	15.2
600	100.0
800	81.8
1000	57.6
1200	18.2
1400	12.1

Slope (°)	Standardized Score
2	26.7
4	46.7
6	73.3
8	66.7
10	46.7
12	100.0
14	80.0
16	53.3
18	60.0
20	26.7
22	33.3
24	6.7
26	0.0
28	6.7

Curvature	Standardized Score
-4	0
-3.5	0
-3	0
-2.5	0
-2	0
-1.5	0
-1	1.9
-0.5	15.1
0	100.0
0.5	52.8
1	7.5
1.5	0
2	0
2.5	0
3	0
3.5	0
4	0

Flow Accumulation	Standardized Score
1	77.1
10	100.0
100	62.9
1000	20.0
10000	8.6
> 10000	0

Lineament Density Set 1	Standardized Score
0	0
10	42.3
20	76.9
30	80.8
40	100.0
50	46.2
60	7.7
70	7.7
80	0
90	0
100	0
110	0

Lineament Density Set 2	Standardized Score
0	0
10	15.4
20	19.2
30	61.5
40	26.9
50	100.0
60	92.3
70	3.8
80	11.5
90	15.4
100	15.4
110	0

Lineament Density Set 3	Standardized Score
0	0
10	27.7
20	57.4
30	100.0
40	14.9
50	0
60	0
70	0
80	0
90	0
100	0
110	0

* the bin value represents the upper bin limit (e.g., elevation BIN 200 has a bin interval of 0 – 200 masl and BIN 400 has a bin interval of >200-400 masl.

Table A12: Okanagan unconsolidated bin intervals and the standardized raster scores.*

Elevation	Standardized Score
200	0.0
400	100.0
600	56.0
800	3.8
1000	9.3
1200	0.0
1400	0.0
1600	0.0
1800	0.0

Slope	Standardized Score
2	100.0
4	61.2
6	19.7
8	7.5
10	10.2
12	4.8
14	2.7
16	2.0
18	0.0
20	0.0
22	0.7
24	0.0
26	0.0
28	0.7
> 28	0.0

Flow Accumulation	Standardized Score
1	65.0
10	100.0
100	37.8
1000	10.5
10000	2.1
100000	0.0

TWI	Standardized Score
2	0.0
4	0.0
6	42.6
8	100.0
10	15.9
12	5.1
14	0.6
16	0.0
18	0.0

Stream Proximity	Standardized Score
100	100.0
200	78.8
300	54.5
400	42.4
500	22.2
600	8.1
700	2.0
800	1.0
900	1.0
1000	1.0
>1000	0.0

Confining	Standardized Score
Yes	100.0
No	11.6

Soil Drainage	Standardized Score
Very Rapidly	n/a
rapidly	59.1
well drained	60.2
moderately well	30.1
imperfectly	65.6
poorly	100.0
very poorly	9.7

* the bin value represents the upper bin limit (e.g., elevation BIN 200 has a bin interval of 0 – 200 masl and BIN 400 has a bin interval of >200-400 masl.

Table A13: Fraser Valley unconsolidated bin intervals and the standardized raster scores.

Elevation	Standardized Score
50	100.0
100	13.3
150	0.6
200	1.0
250	0.2
300	0.0
350	0.0
400	0.0

Slope	Standardized Score
2	100.0
4	58.0
6	23.1
8	10.5
10	2.4
12	3.1
14	1.0
16	0.0
18	0.7
20	0.3
22	0.0
24	0.0
26	0.0
28	0.7

Flow Accumulation	Standardized Score
1	73.0
10	100.0
100	46.8
1000	20.7
10000	5.1
100000	2.5
1000000	0.4

TWI	Standardized Score
2	0
4	0
6	36.8
8	100
10	9.1
12	2.3
14	1
>14	0

Stream Proximity	Standardized Score
100	100.0
200	68.6
300	26.5
400	15.9
500	12.7
600	8.2
700	5.3
800	1.2
900	2.0

Soil Drainage	Standardized Score
Very Rapidly Drained	n/a
Rapidly Drained	70.4
Well Drained	70.4
Moderately Well Drained	82.5
Imperfectly Drained	82.5
Poorly Drained	100.0
Very Poorly Drained	100.0

Confining Aquifer Present	Standardized Score
Yes	100
No	2.5

* Drainage categories with the same standardized score were binned together.

APPENDIX B: FACTOR MAPS FOR THE OKANAGAN

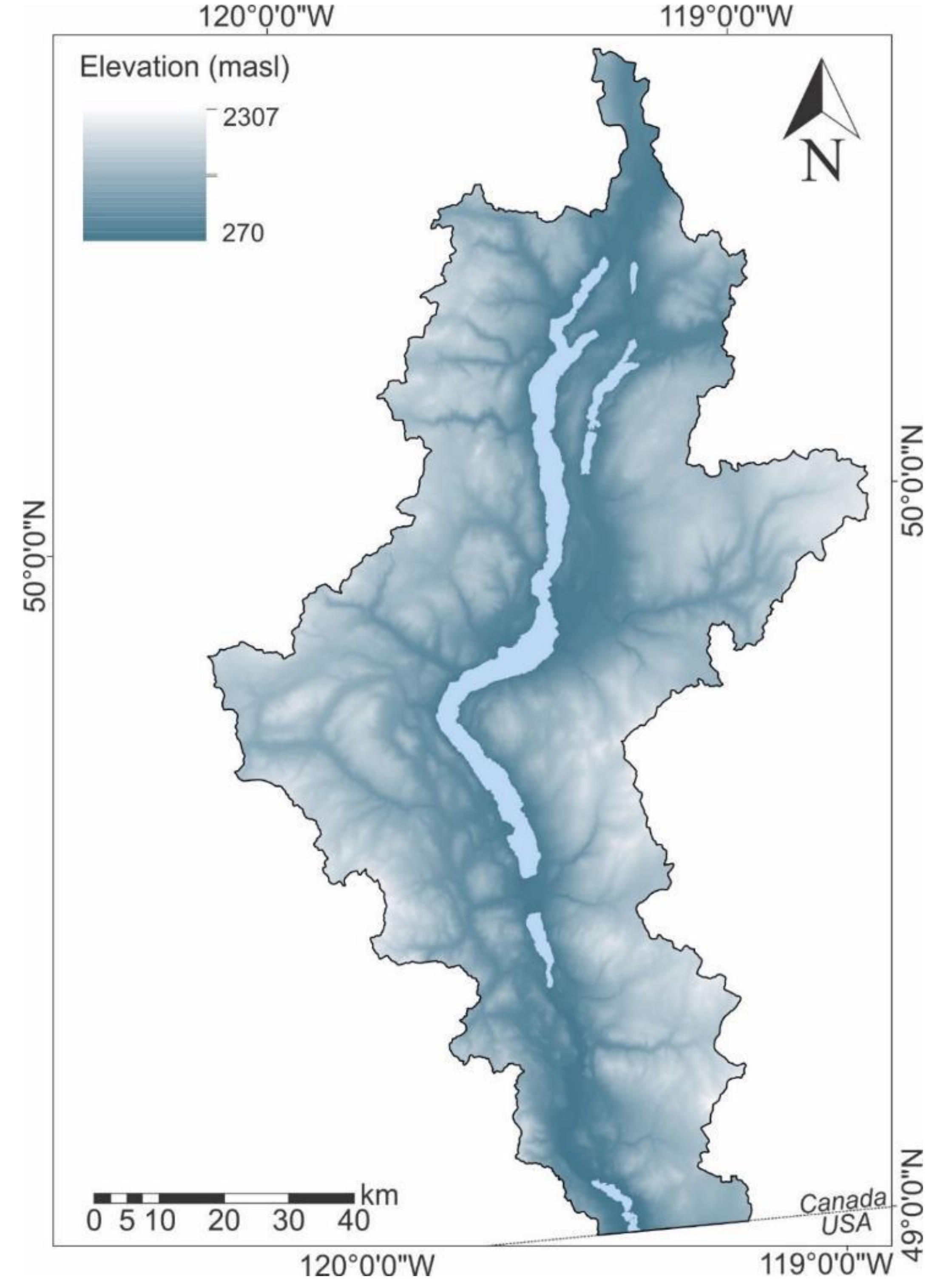

Figure B1: Okanagan DEM.

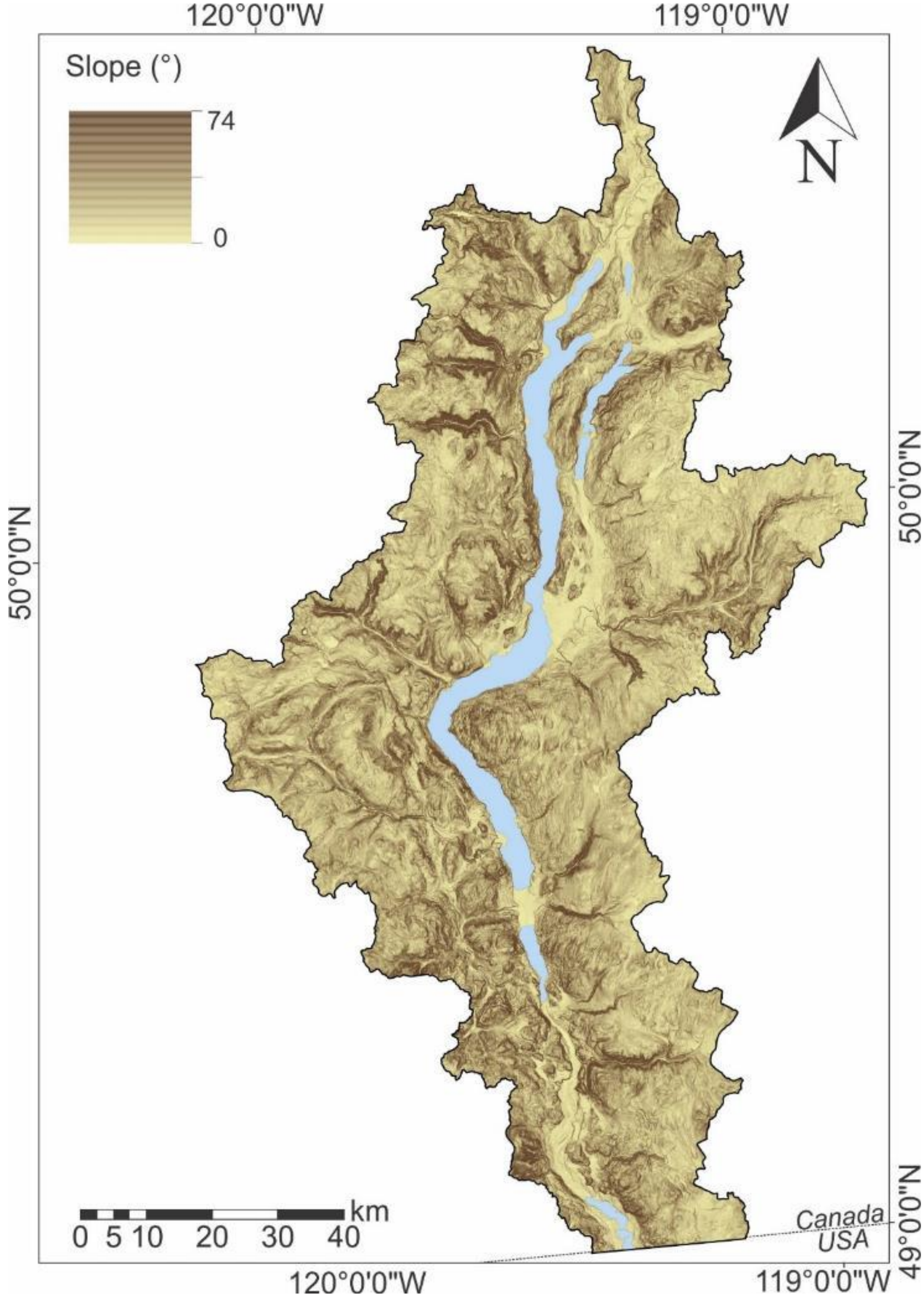

Figure B2: Okanagan slope.

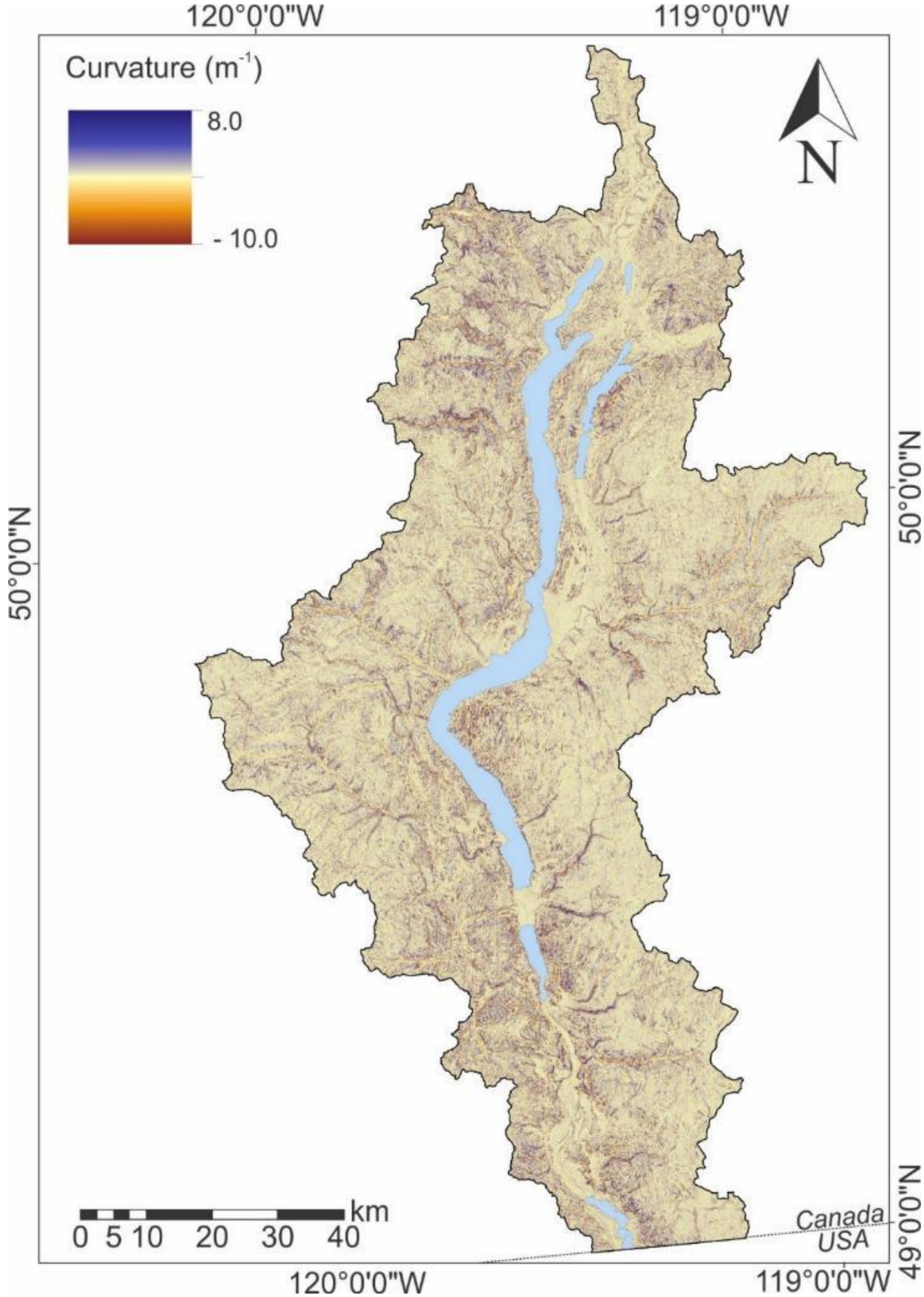

Figure B3: Okanagan curvature.

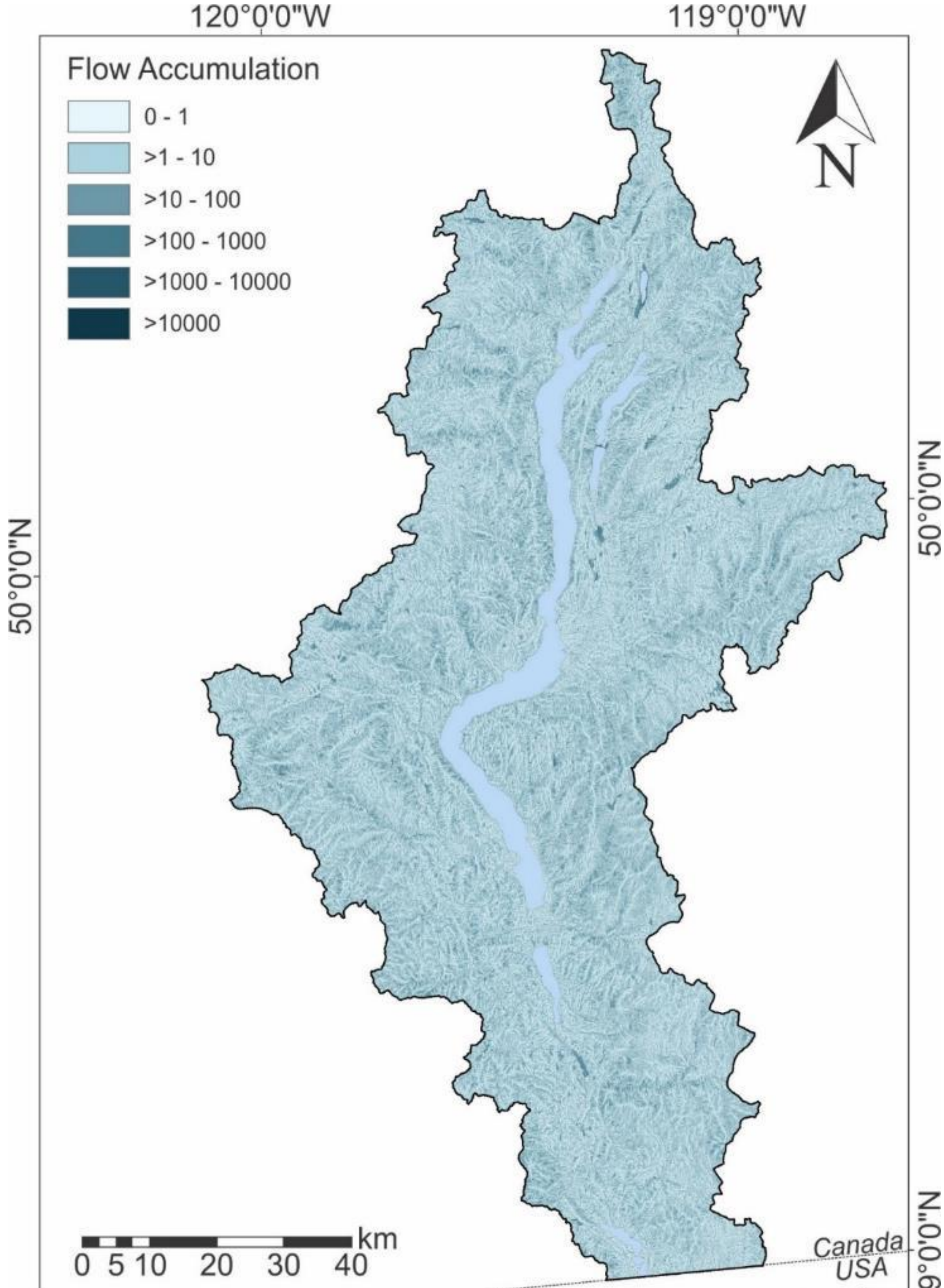

Figure B4: Okanagan flow accumulation.

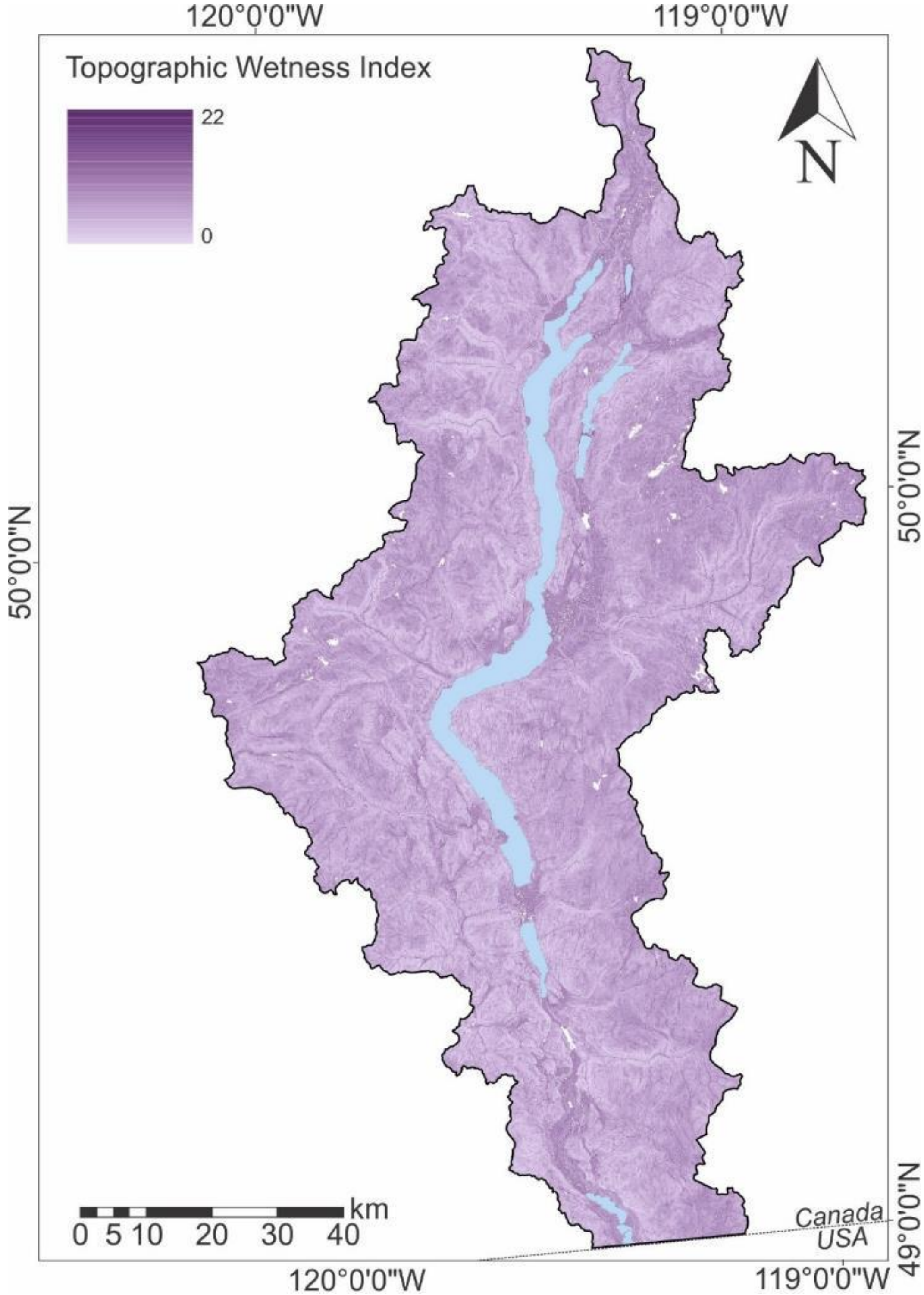

Figure B5: Okanagan topographic wetness index.

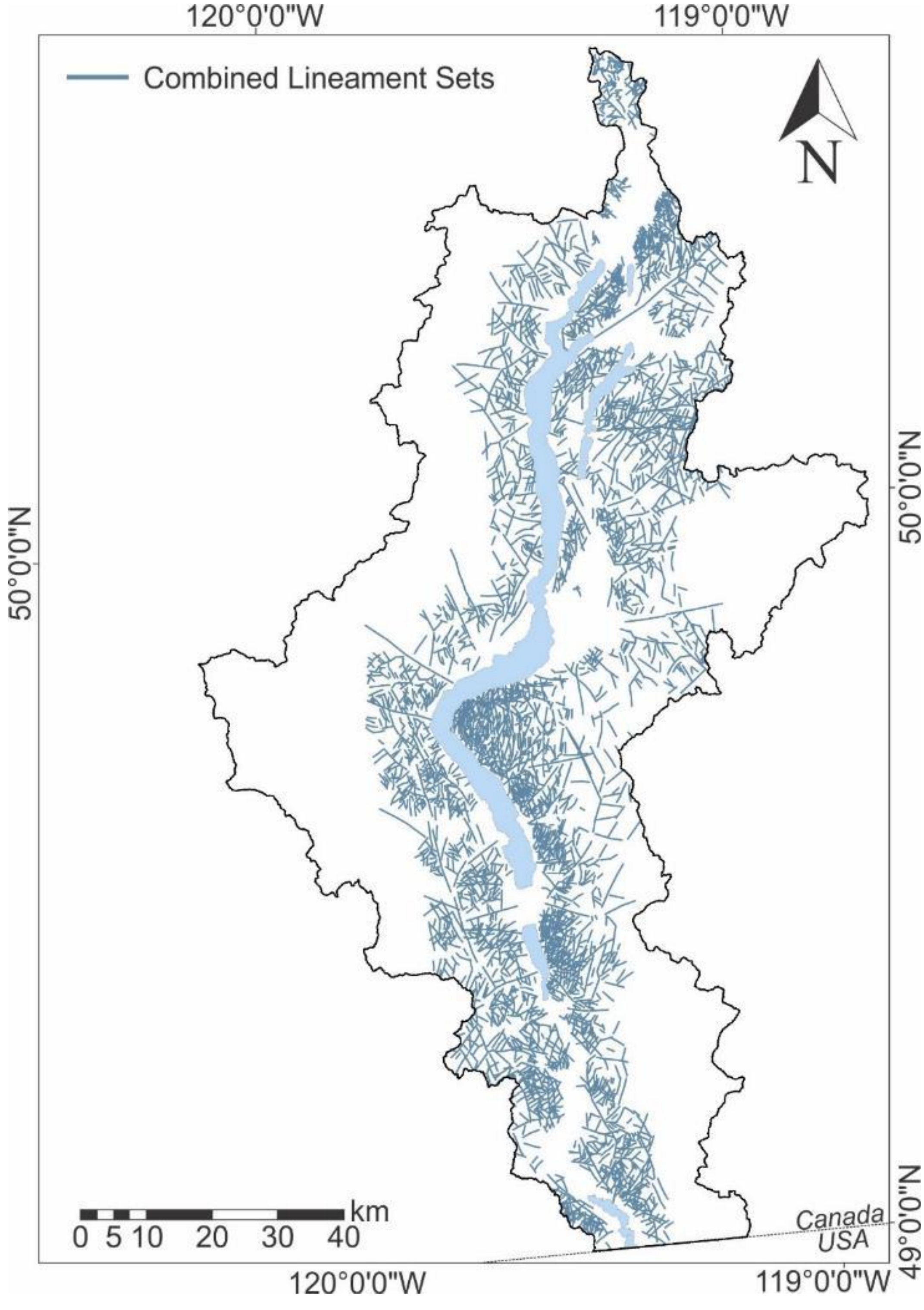

Figure B6: Okanagan lineaments for all sets combined.

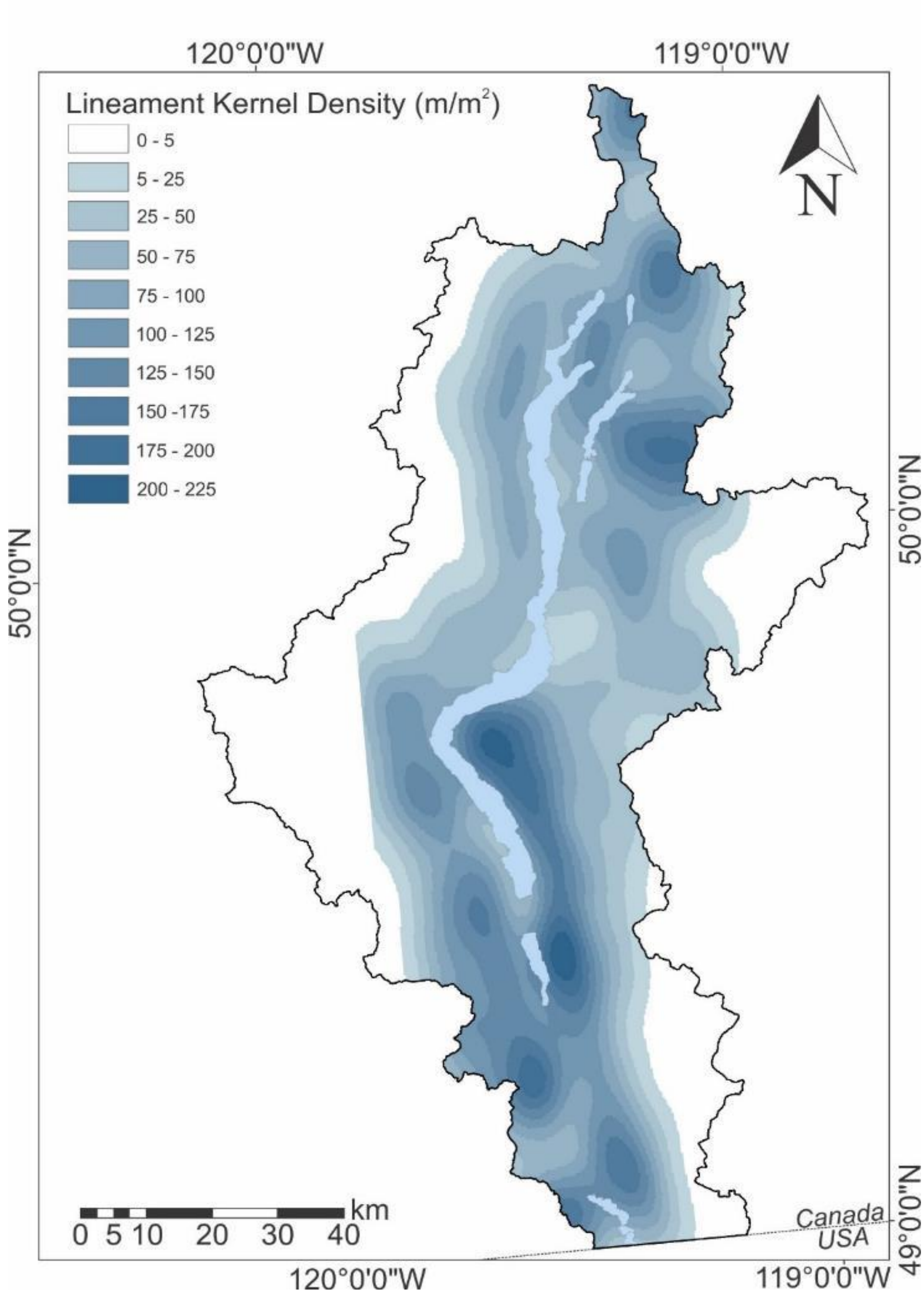

Figure B7: Okanagan lineament kernel densities for all sets combined.

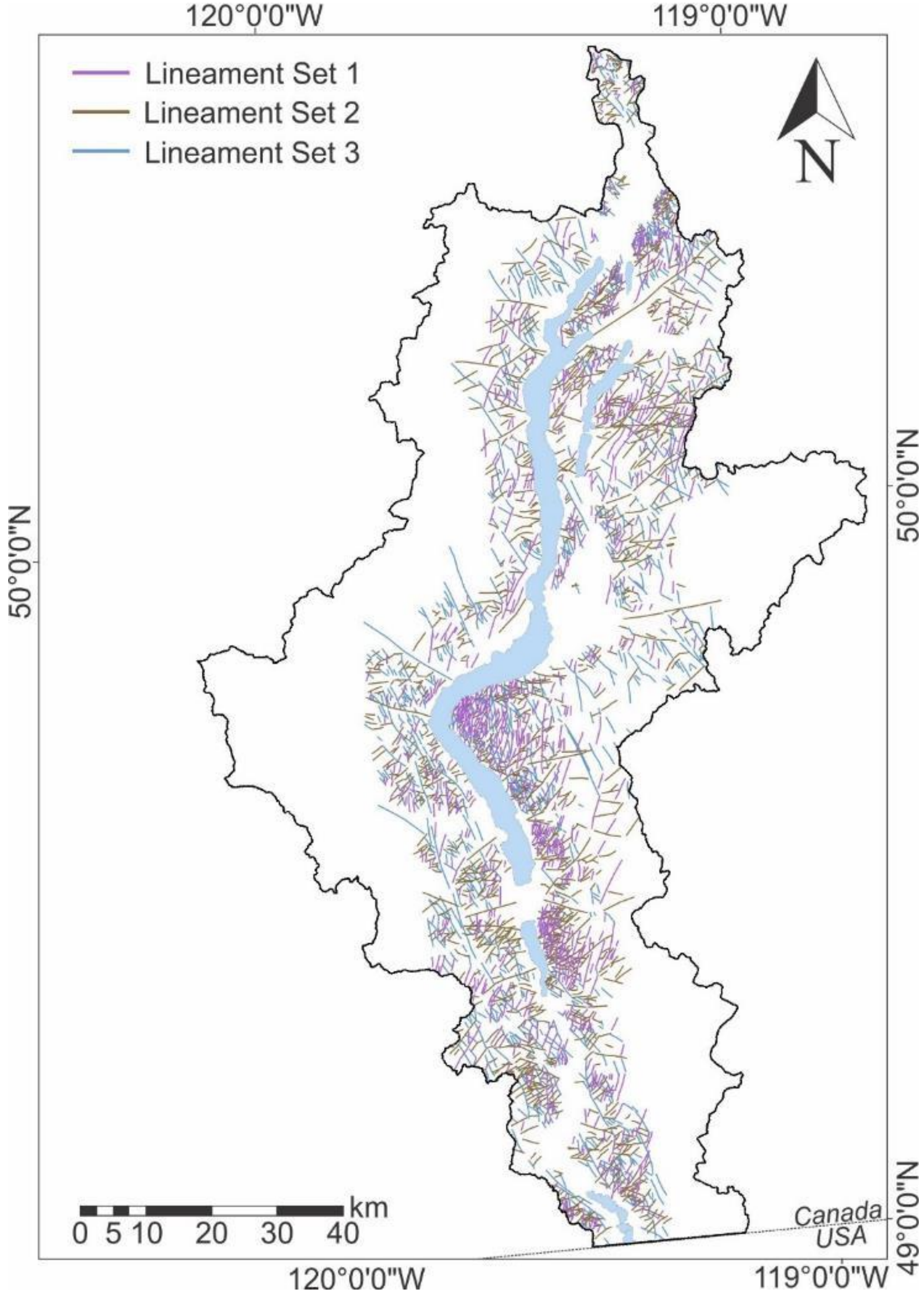

Figure B8: Okanagan lineaments sets.

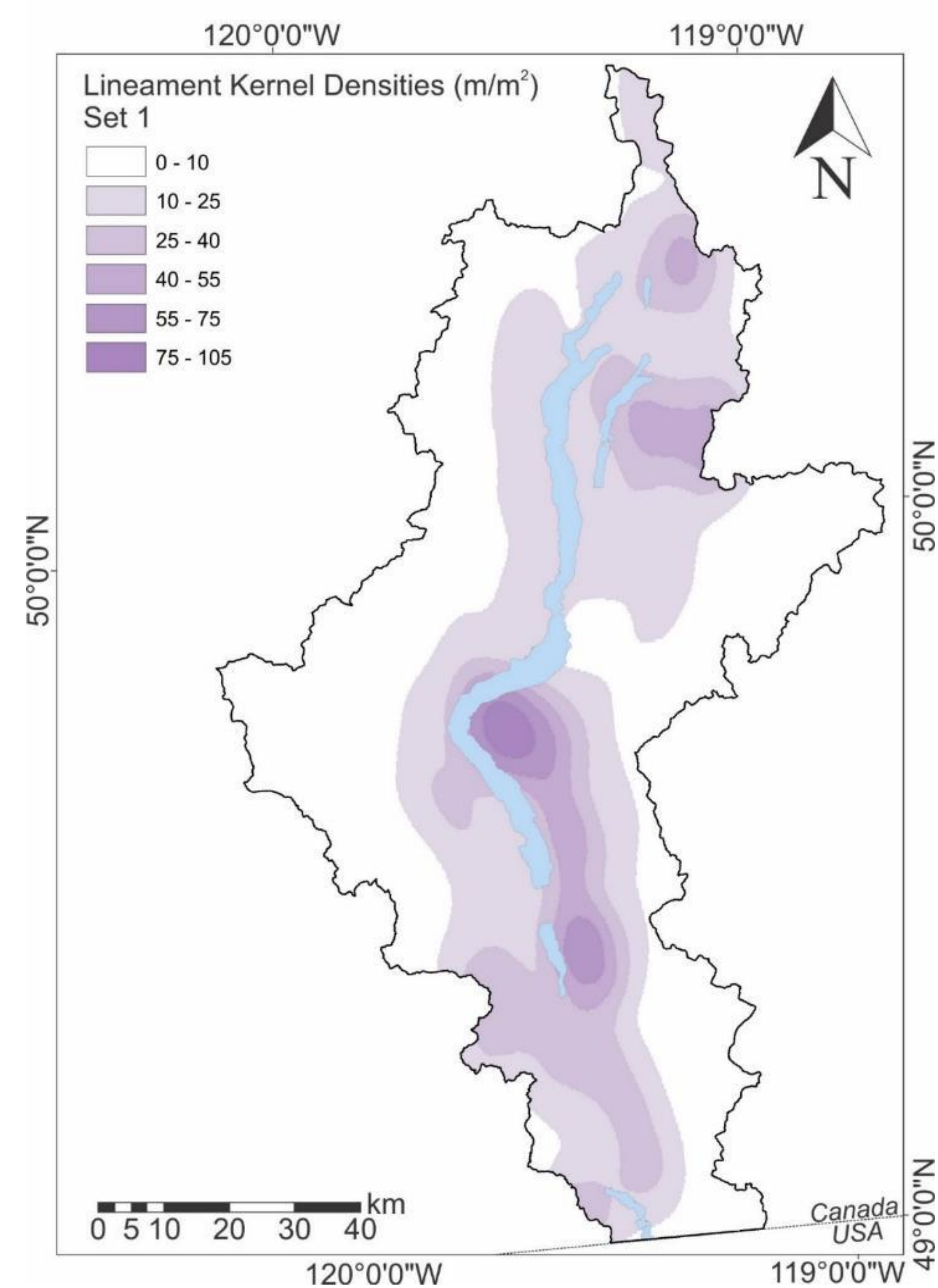

Figure B9: Okanagan lineament kernel density map for set 1.

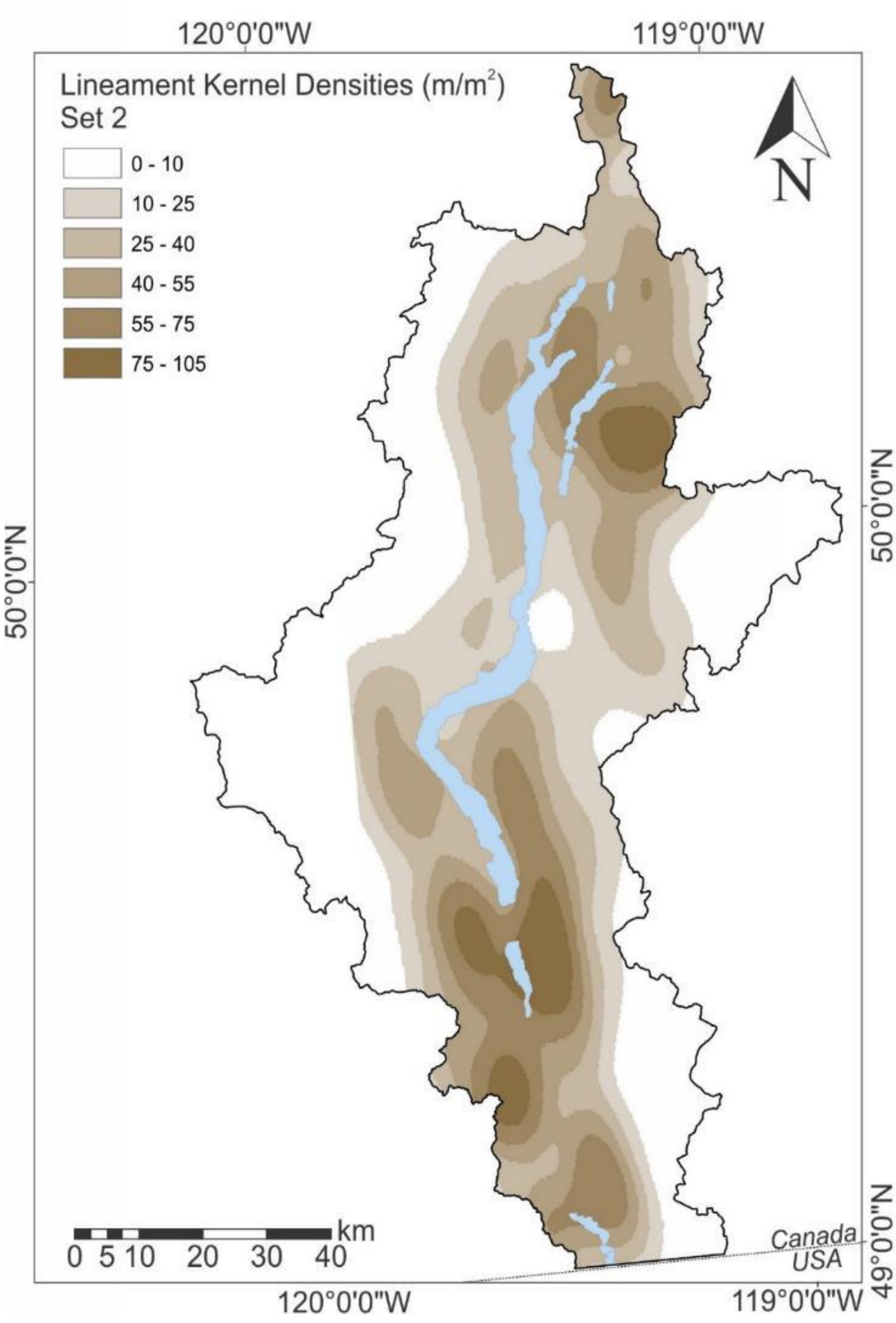

Figure B10: Okanagan lineament kernel density map for set 2.

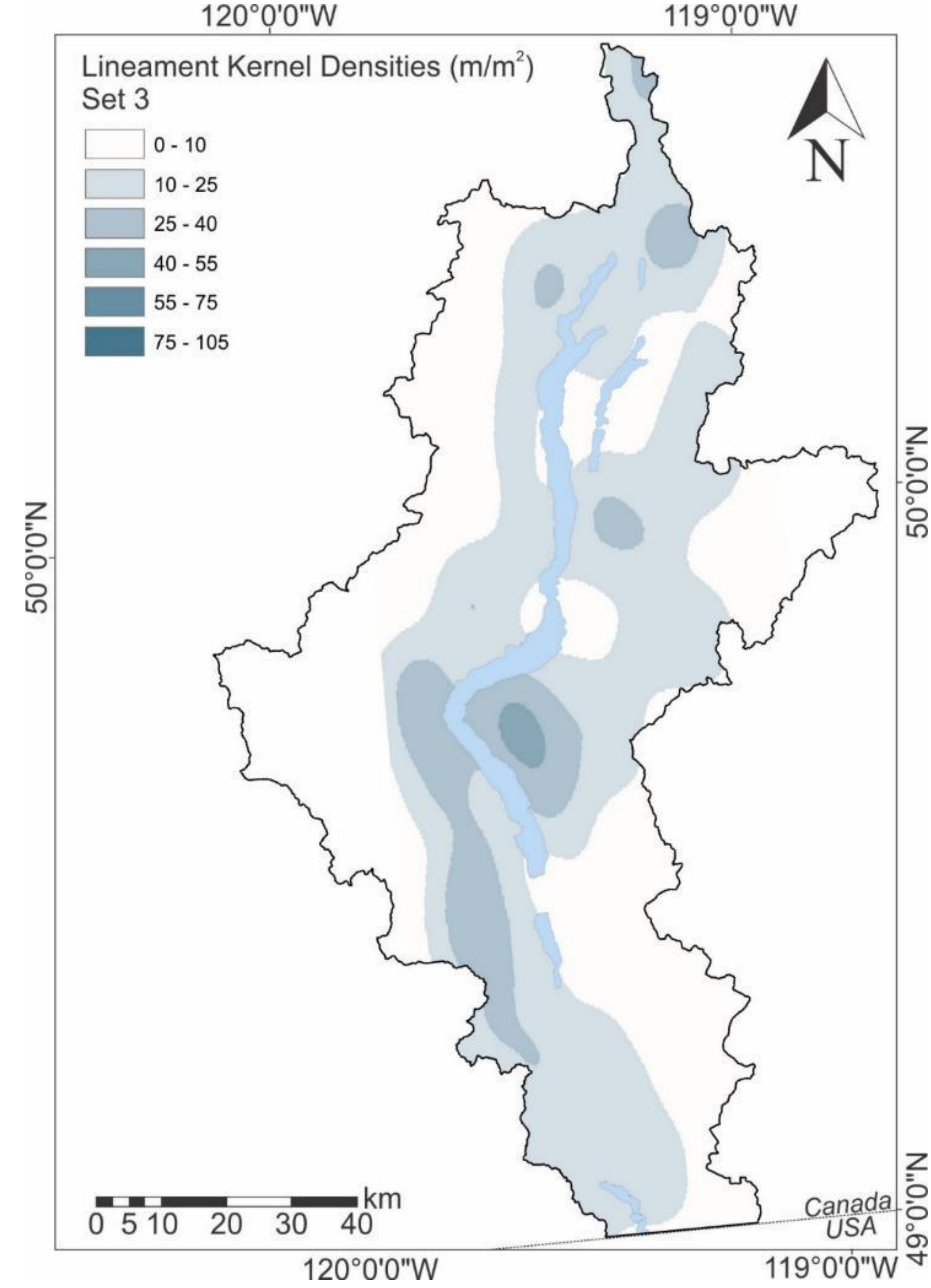

Figure B11: Okanagan lineament kernel density map for set 3.

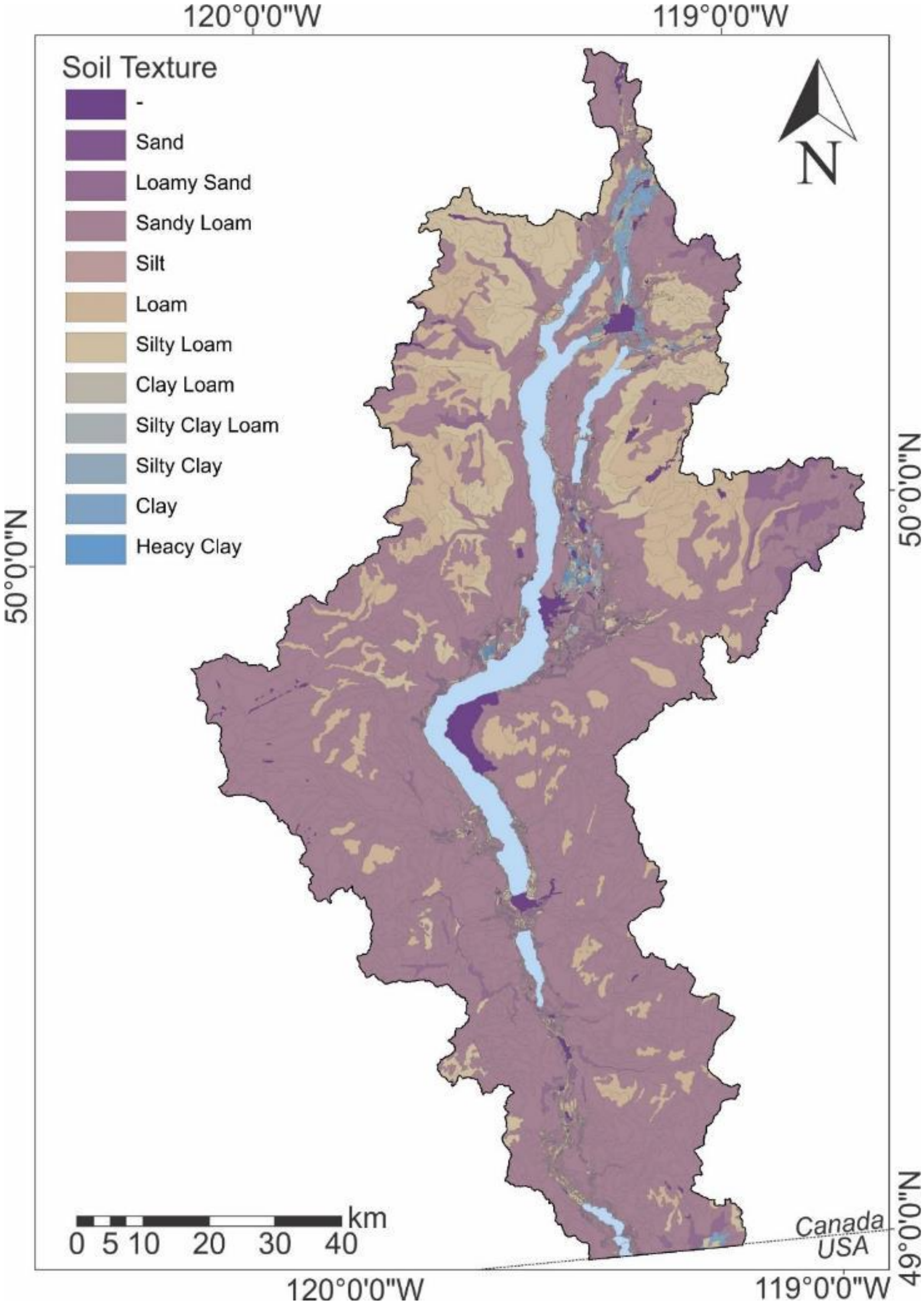

Figure B12: Okanagan soil texture.

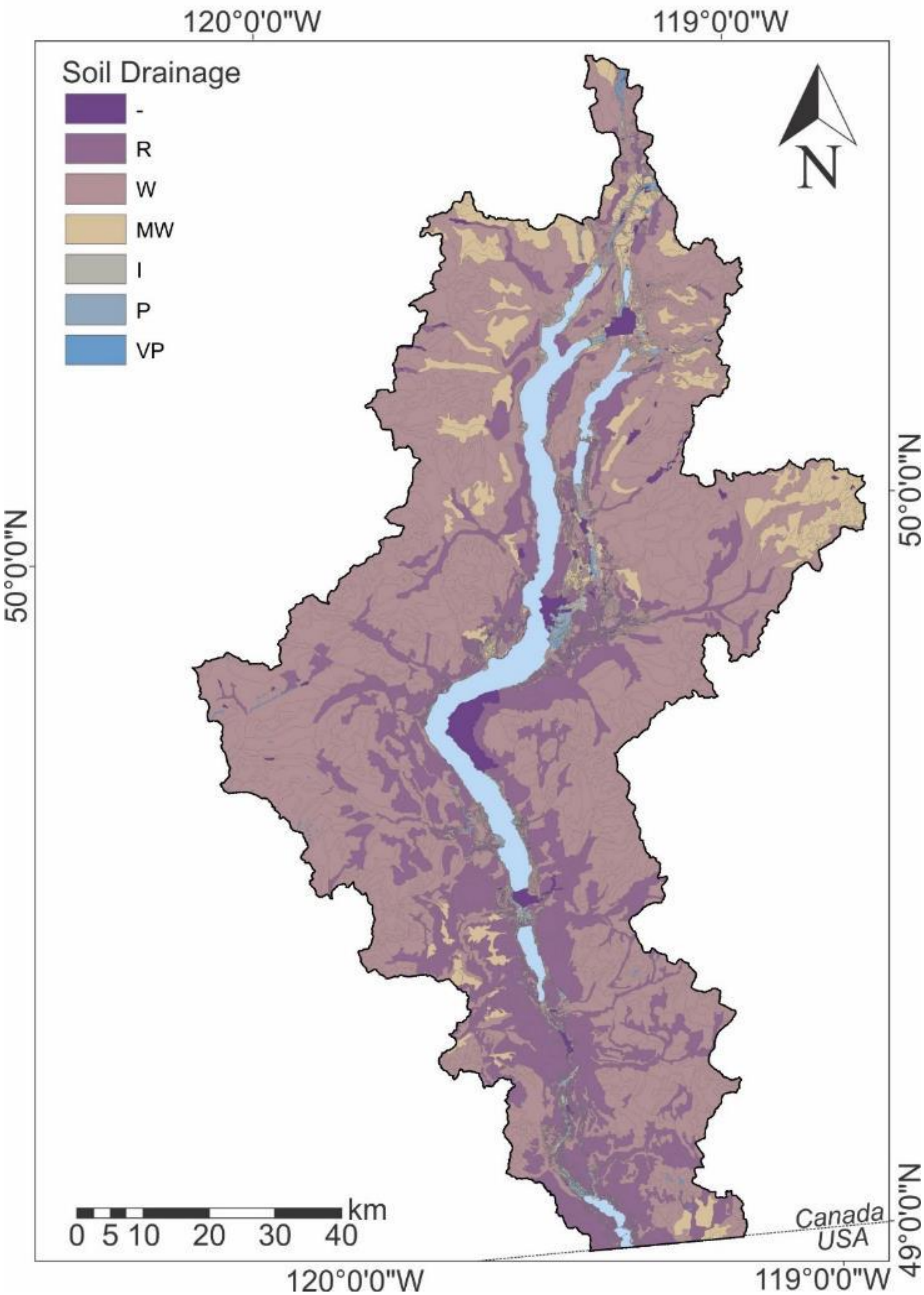

Figure B13: Okanagan soil drainage.

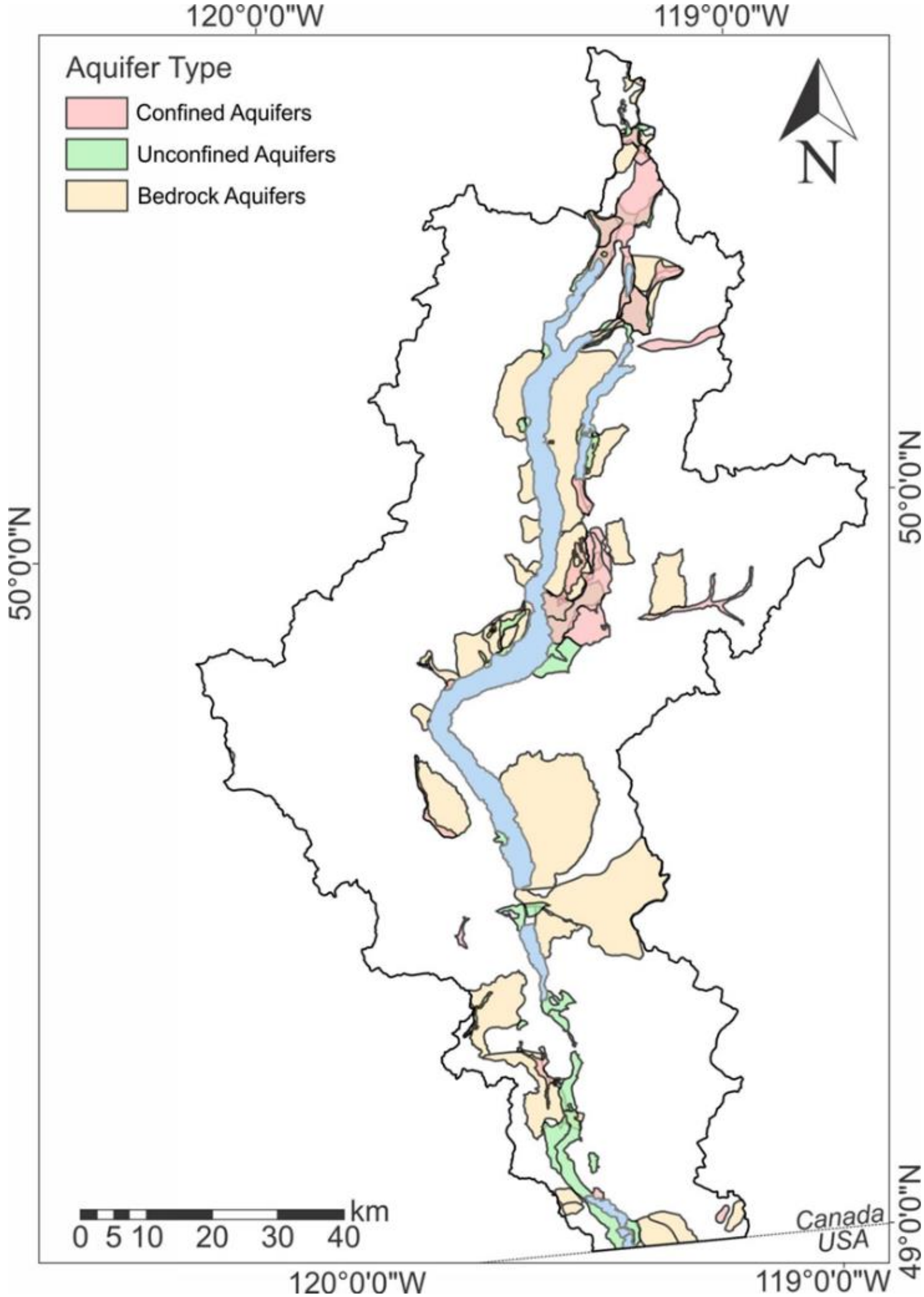

Figure B14: Okanagan aquifers.

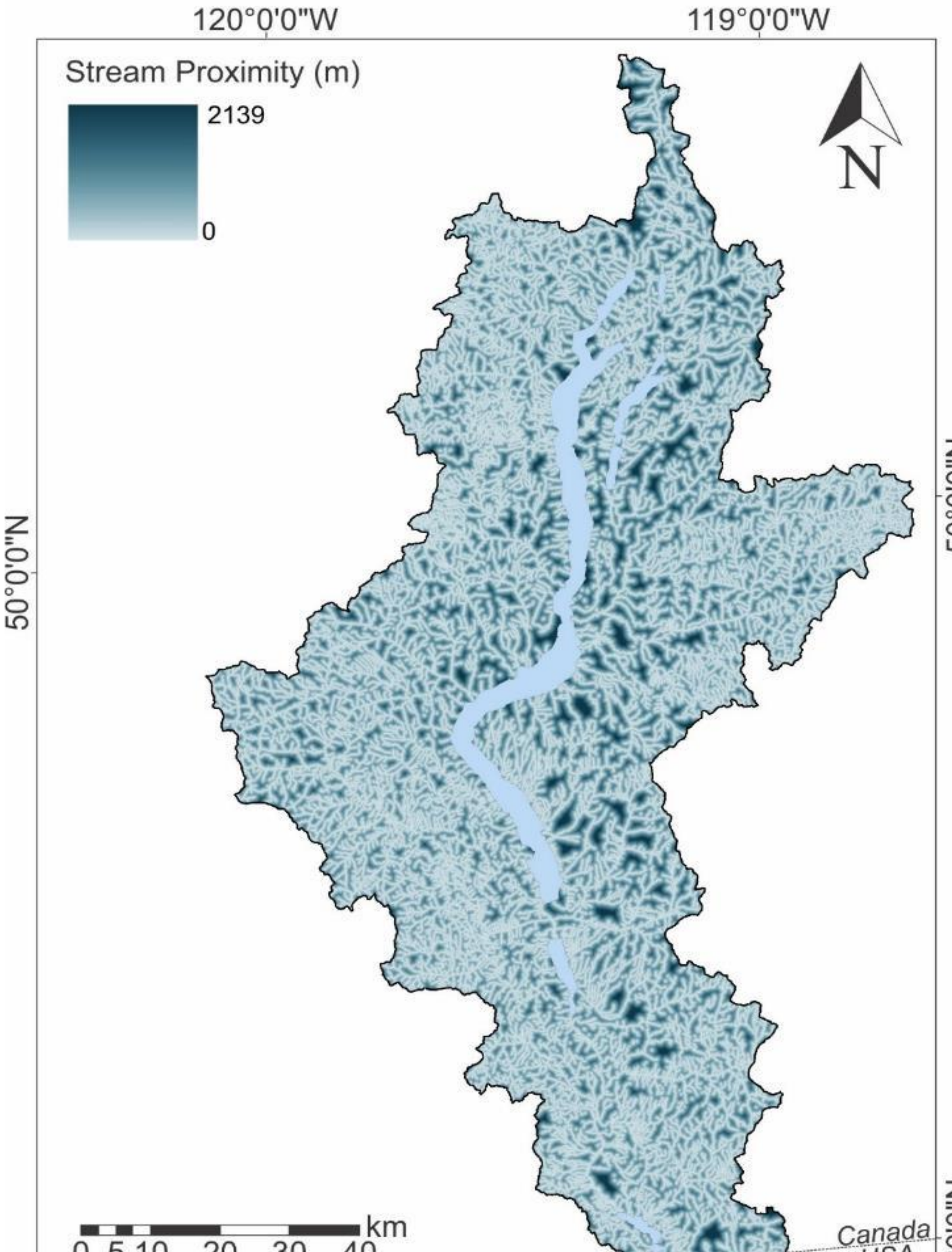

Figure B15: Okanagan stream proximity.

APPENDIX C: FACTOR MAPS FOR THE FRASER VALLEY

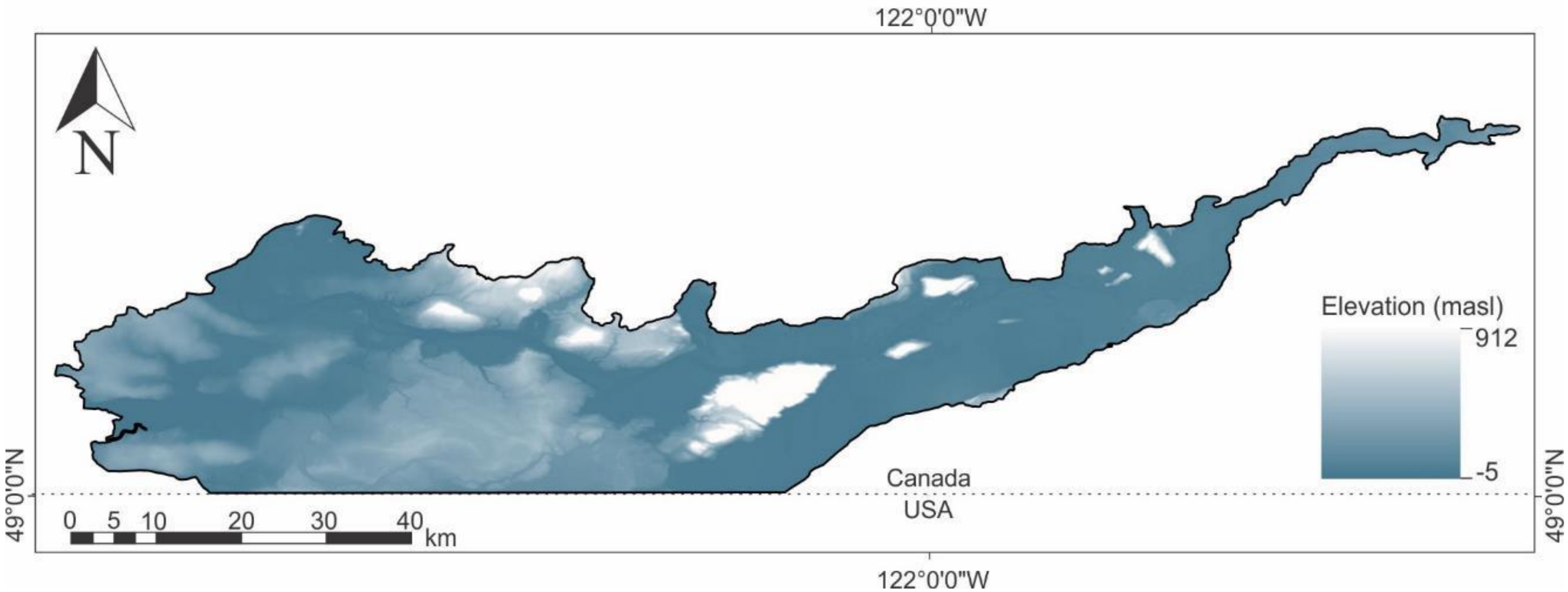

Figure C1: Fraser Valley DEM.

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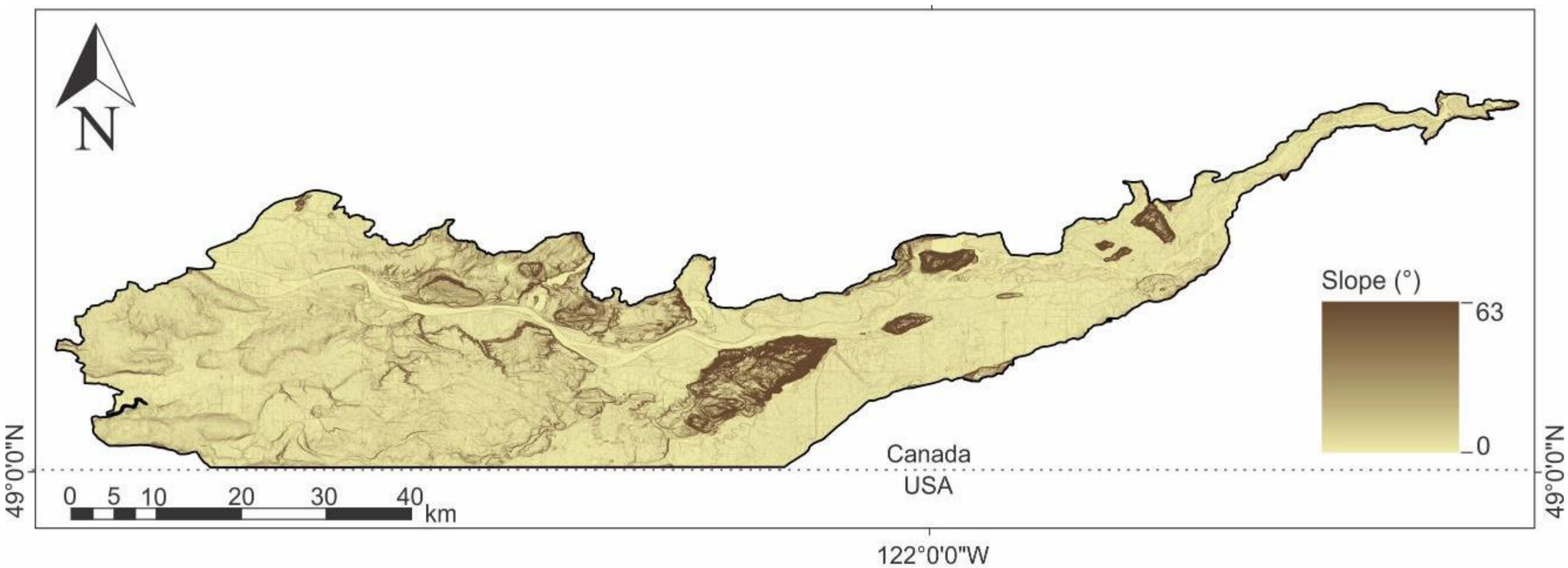

Figure C2: Fraser Valley slope.

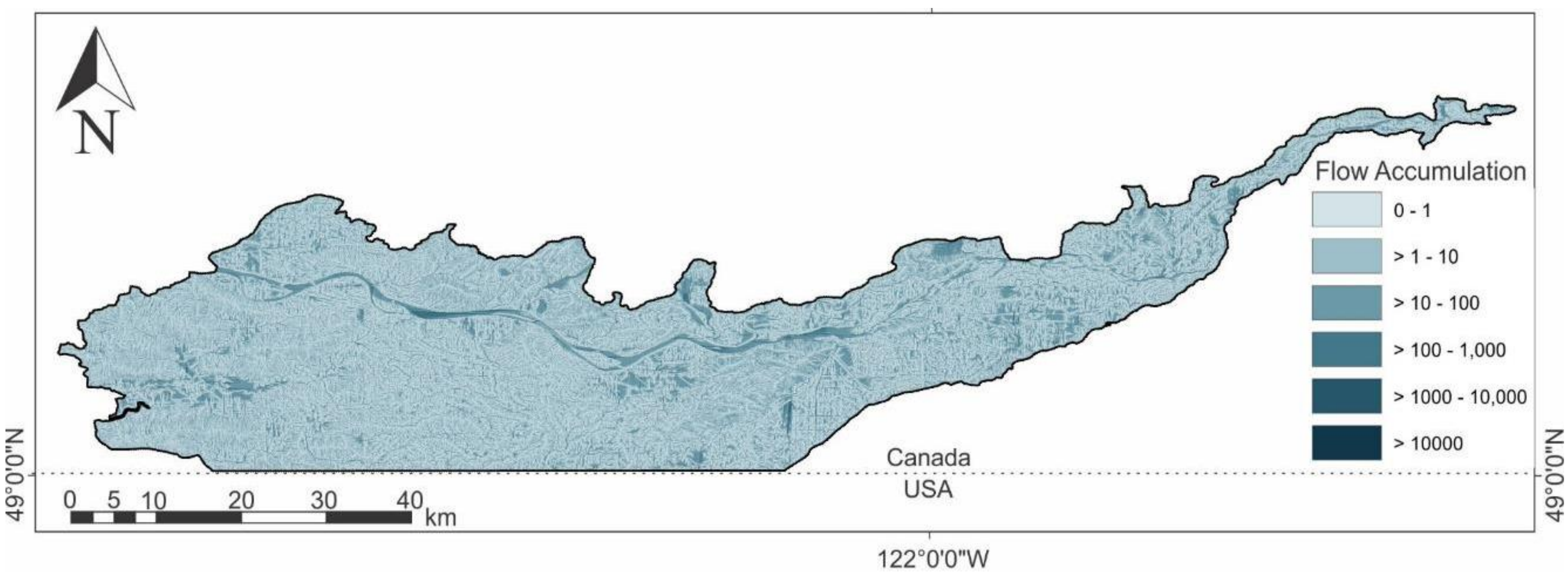

Figure C3: Fraser Valley flow accumulation.

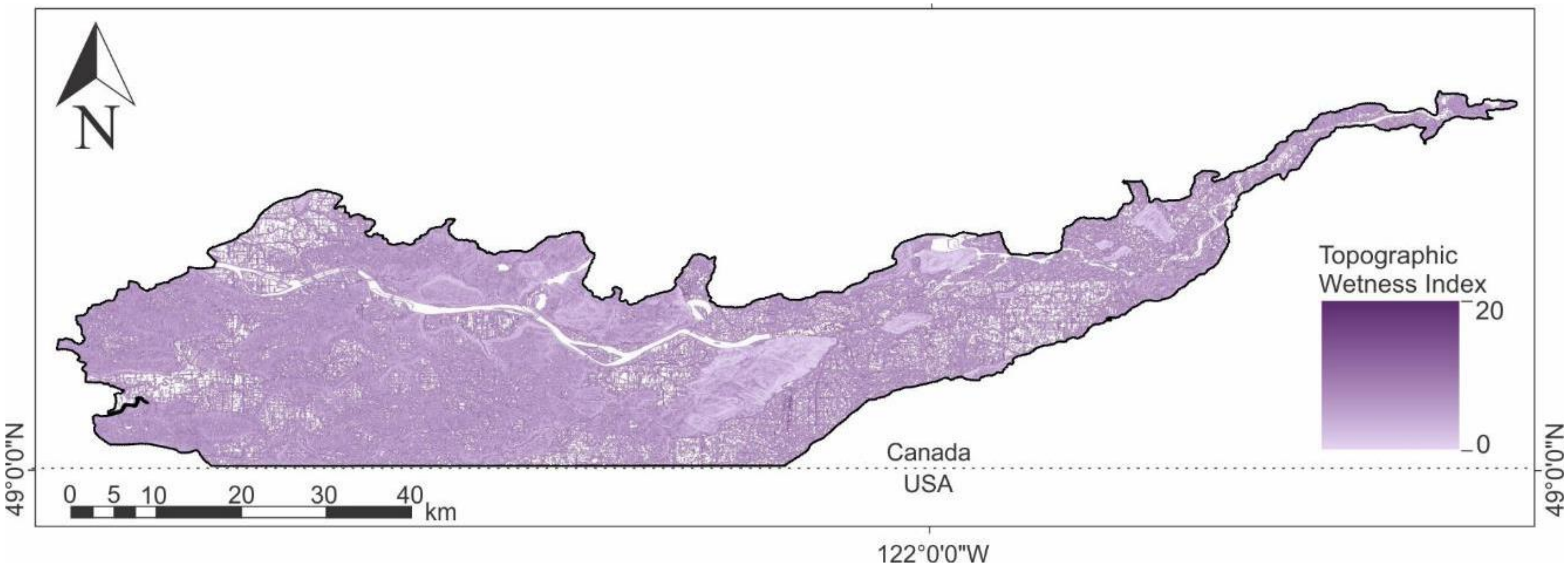

Figure C4: Fraser Valley topographic wetness index.

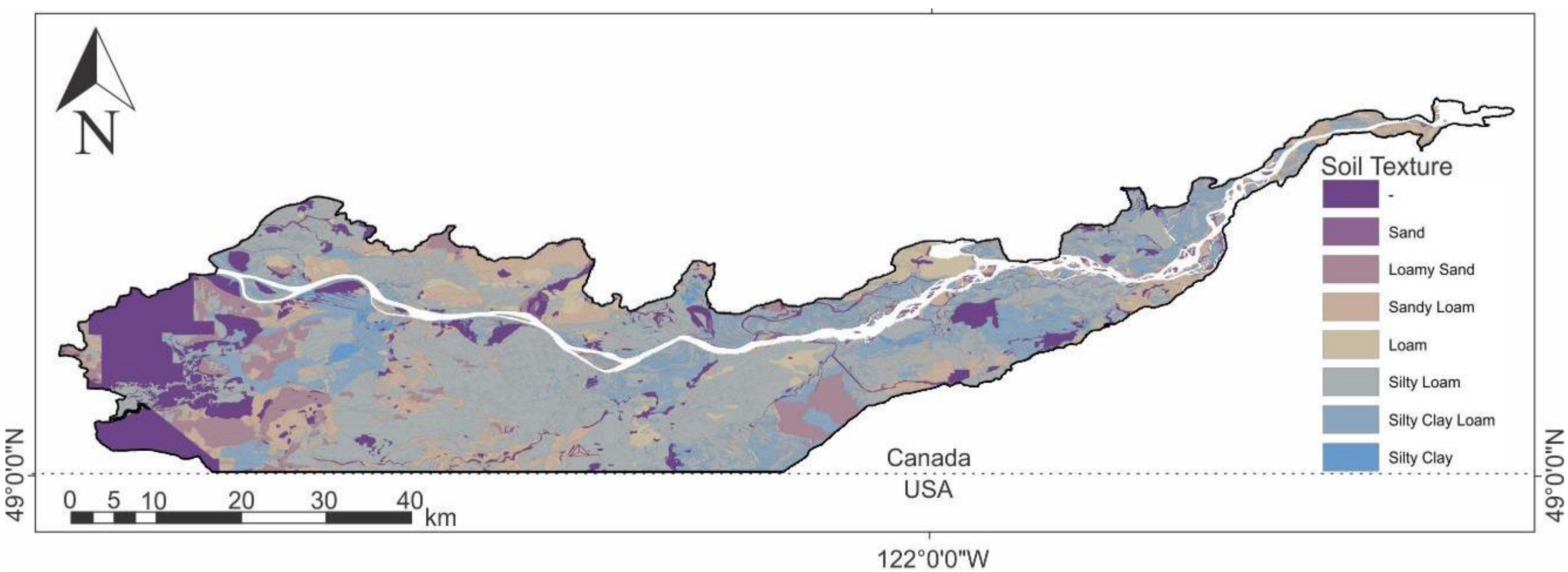

Figure C5: Fraser Valley soil texture.

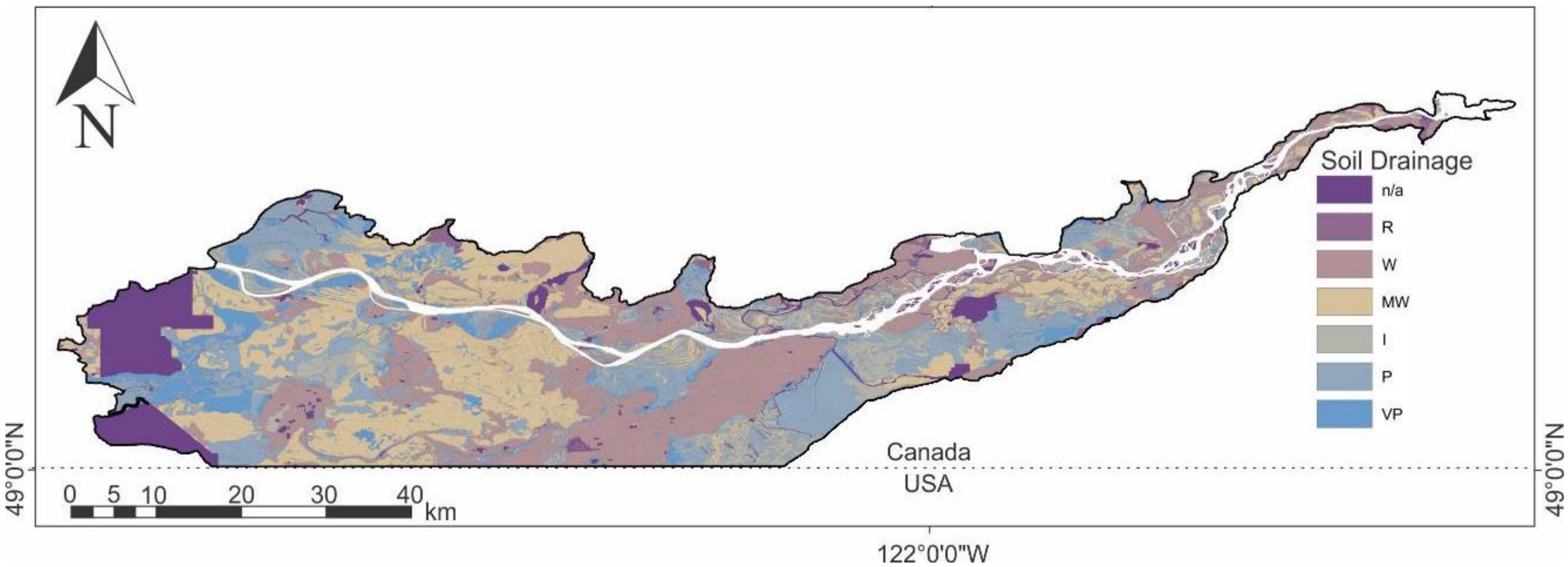

Figure C6: Fraser Valley soil drainage.

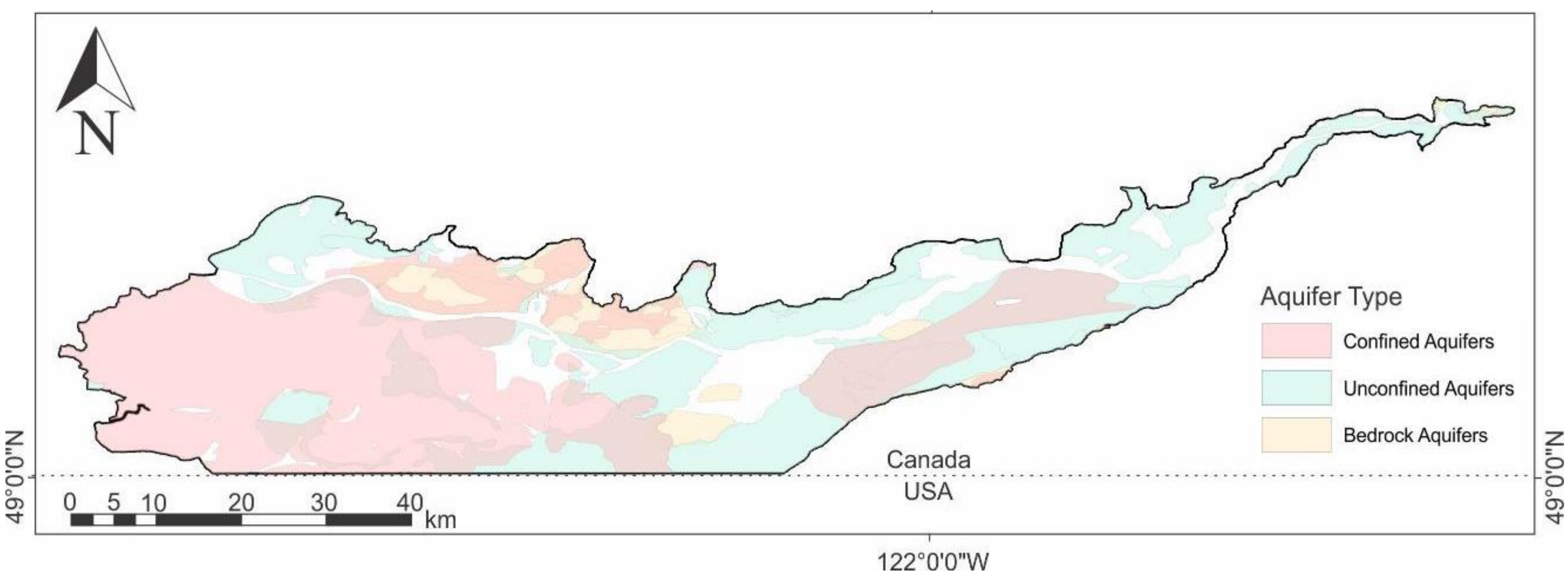

Figure C7: Fraser Valley aquifers.

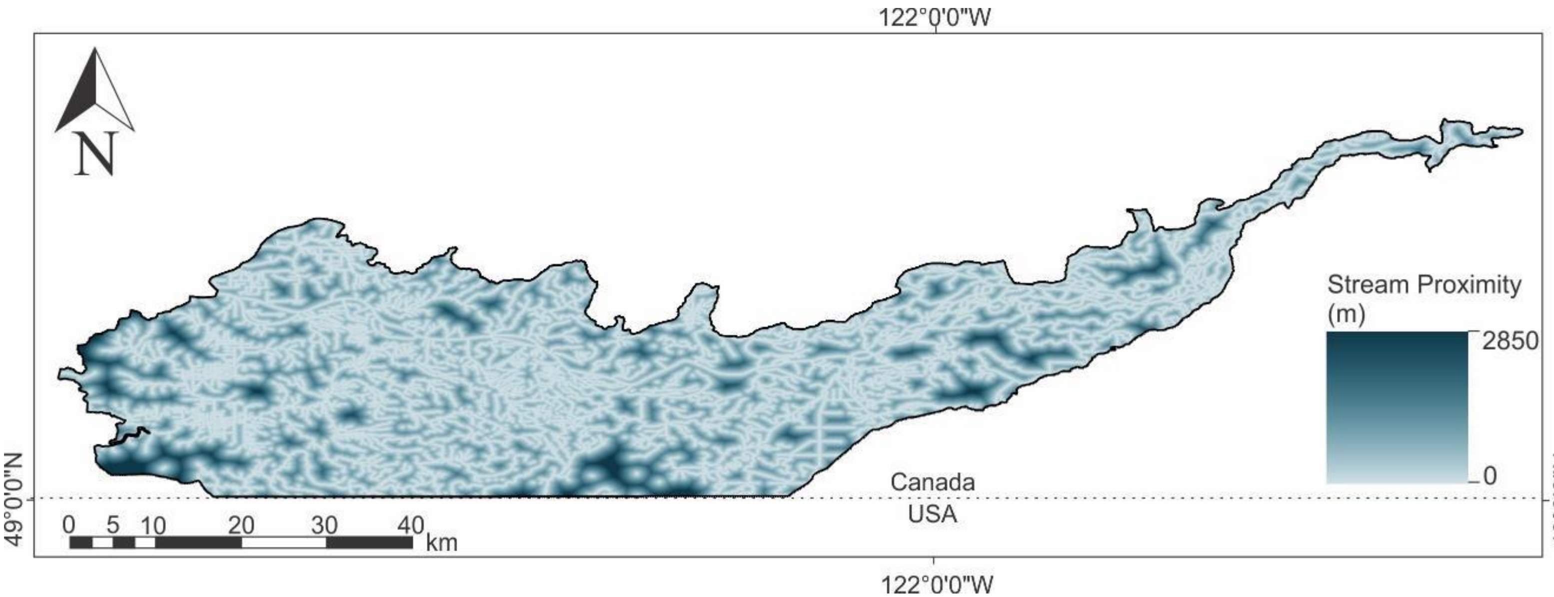

Figure C8: Fraser Valley stream proximity.

APPENDIX D: PERCENT FREQUENCY GRAPHS

Okanagan Bedrock Context

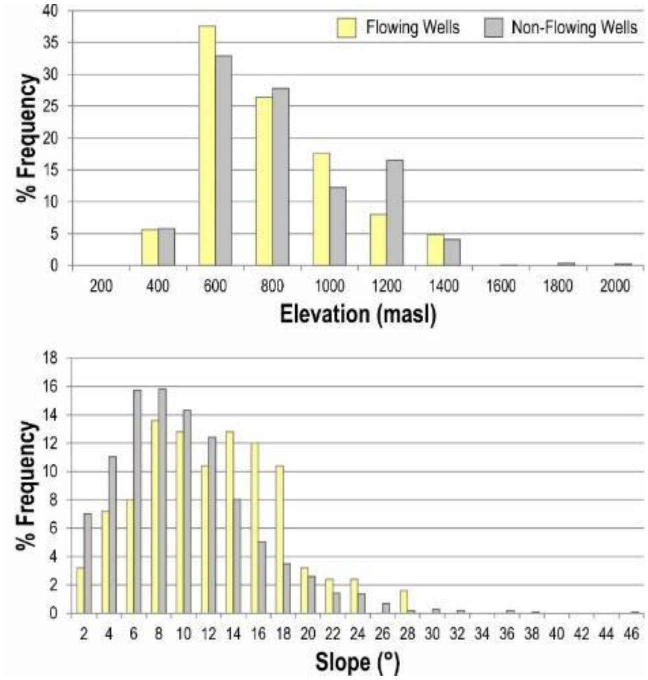

Figure D1: Okanagan bedrock percent frequency graphs of the occurrence of flowing and non-flowing wells for elevation and slope.

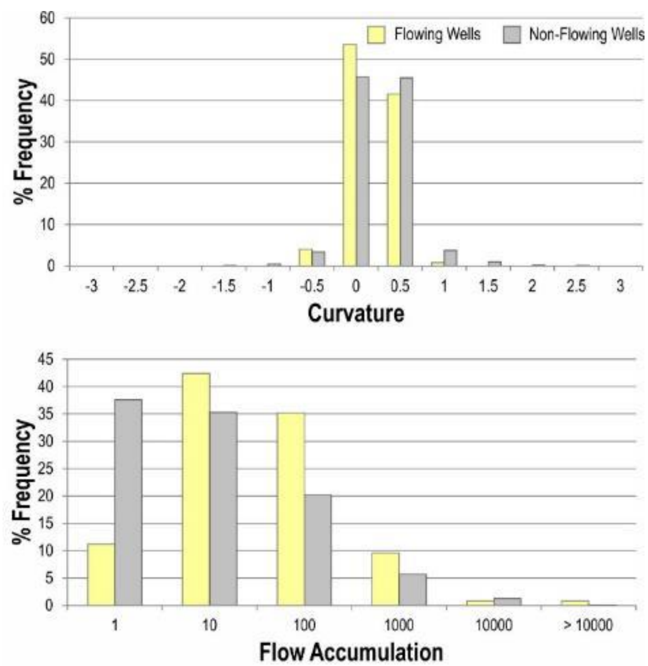

Figure D2: Okanagan bedrock percent frequency graphs of the occurrence of flowing and non-flowing wells for curvature and flow accumulation.

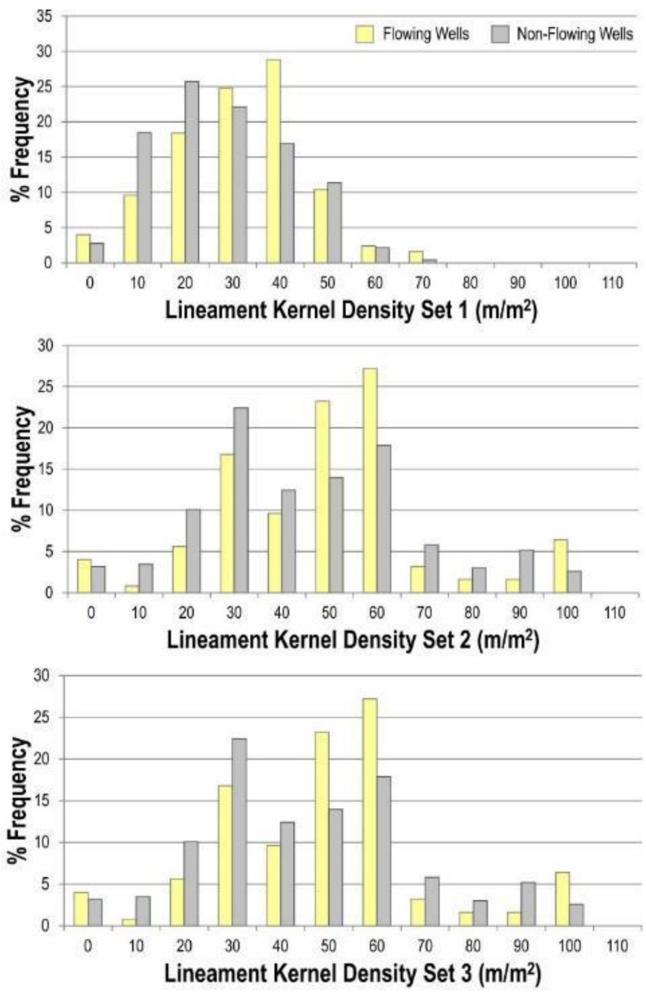

Figure D3: Okanagan bedrock percent frequency graphs of the occurrence of flowing and non-flowing wells for the lineament density sets.

Okanagan Unconsolidated Context

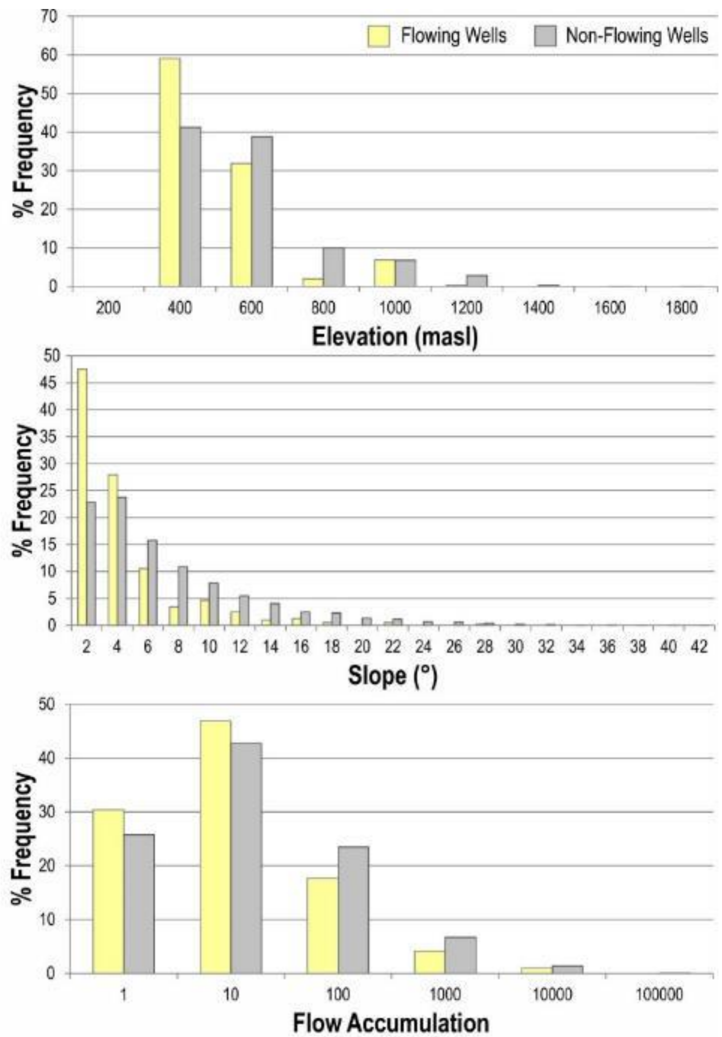

Figure D4: Okanagan unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for the elevation, slope and flow accumulation.

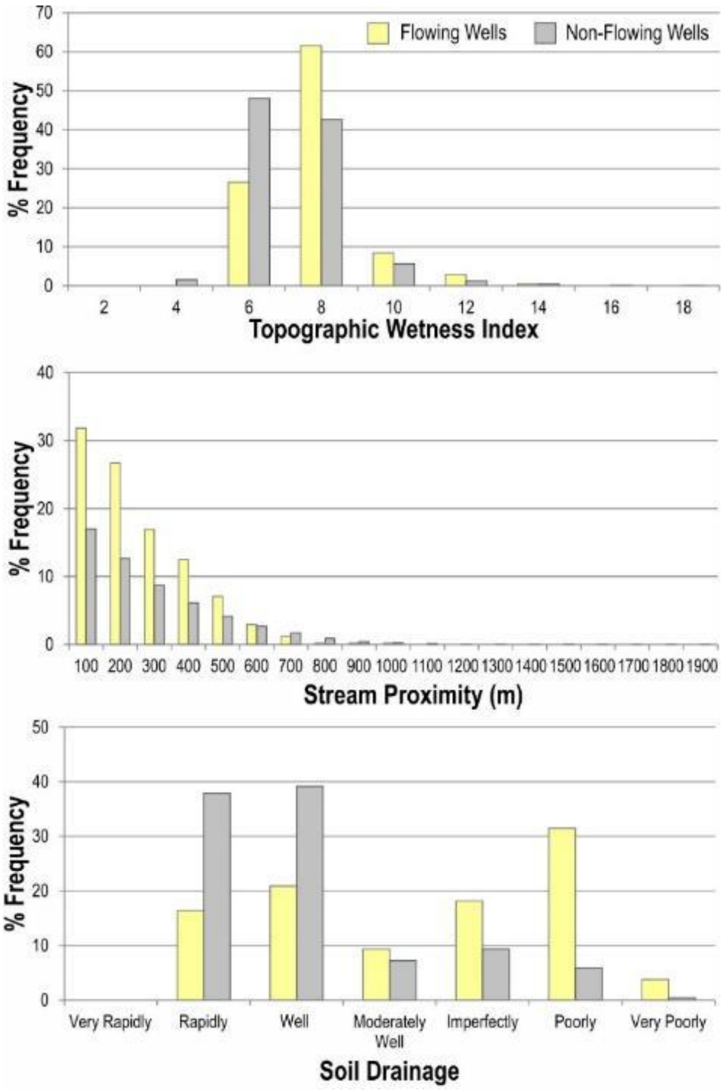

Figure D5: Okanagan unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for the topographic wetness index, stream proximity and soil drainage.

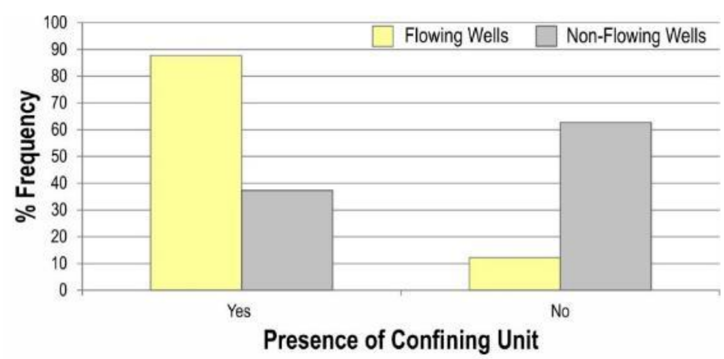

Figure D6: Okanagan unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for presence of a confining unit.

Fraser Valley Unconsolidated Context

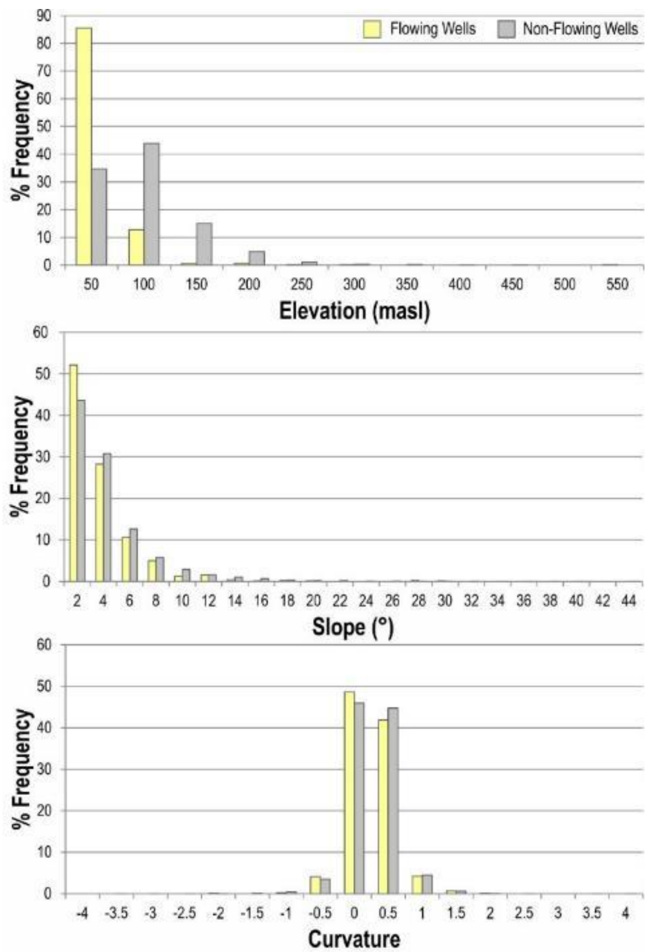

Figure D7: Fraser Valley unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for elevation, slope, and curvature.

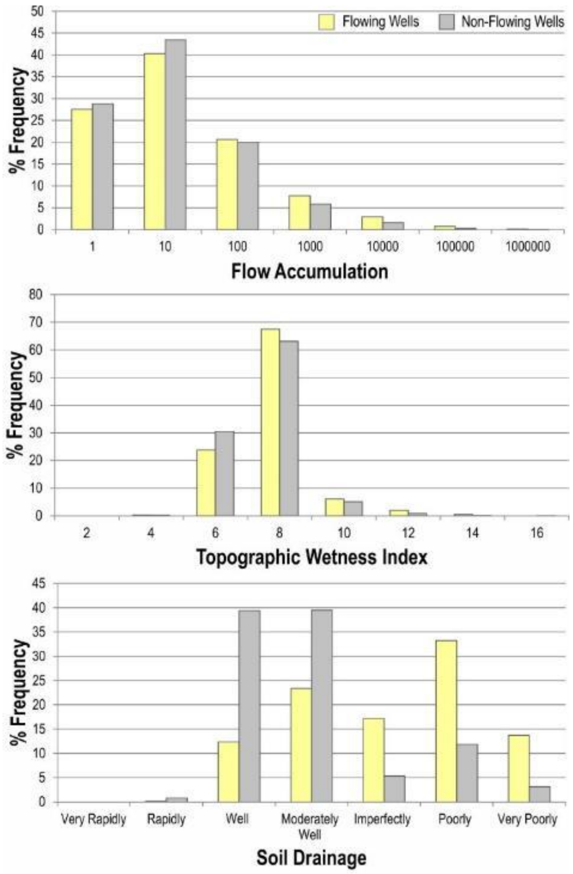

Figure D8: Fraser Valley unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for flow accumulation, topographic wetness index, and soil drainage.

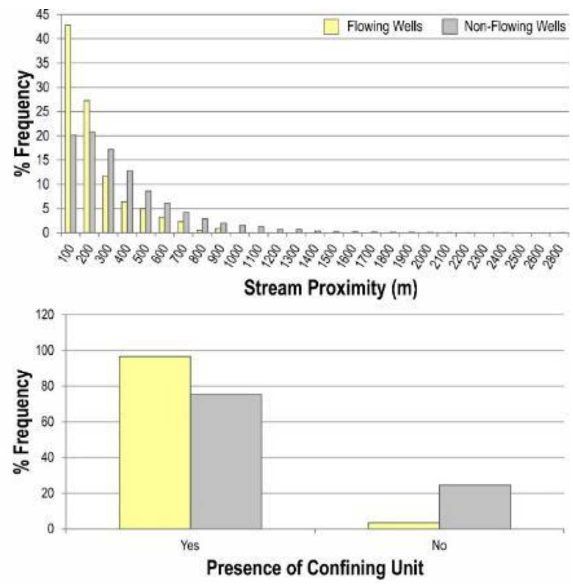

Figure D9: Fraser Valley unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for stream proximity and the presence of a confining unit.

APPENDIX E: RECOMMENDATIONS FOR THE WELL INSPECTION REPORT

One of the project tasks was to review the existing Well Inspection Form (Form) to include information from inspection of flowing artesian wells. We offer the following input on the draft Form for the ENV/FLNRORD Team's consideration:

- In the paragraph immediately under the section entitled: Additional Information Requirements for Artesian Wells, we suggest making each question a line item and provide space immediately below to record the observation.
- For "Artesian Flow rate or pressure (if known)", include units for pressure.
- Consider including an additional question after "Leakage around casing (s)" to describe where the artesian flow is draining to.
- Consider including an additional question after "Leakage around casing (s)" about the risk of backflow occurring (back down the well).
- Allow more space on the Form for a site diagram to be drawn in the field and provide instruction for what to include in the diagram (e.g., show the location of the well, relevant works, building and geographical features, and where artesian flow is draining to).

In addition to the information recorded on the Form, we also identified additional questions that may be helpful in assessing compliance and informing any statutory directions to comply with stopping or controlling flow. These questions are presented below and perhaps could be completed separate from the Form (we understand the Form is to be provided to the well owner):

Fact-based:

- Is the well drilled into an unconsolidated or fractured bedrock aquifer?
- Is a confining unit identifiable from the well log?
- Does the well have a surface seal?
- Does the well have a well screen?
- Is the well located in a low-lying area?
- Is there high topographic relief in local surrounding area?

Interpretive:

- Any negative impacts as a result of uncontrolled flow?
- If the flow drains into a stream or wetland, is the flow important to sustaining the aquatic ecosystem?
- Are there risks/issues as a consequence of where the flow is currently draining to?
- Does infrastructure on the property limit or affect remedial options?
- Does the situation meet the test of s52(6)? What are the exceptional circumstances?
- Can the flow be managed as is? With improvements? What specific improvements are required (e.g., raise the stick-up; install a packer system (e.g., Well Buster); decommission the well; other?)?
- Is a licence required for the use of the water?
- Willingness and capacity of the well or land owner to comply?