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

by

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Declaration of Committee

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Abstract

Drilling into an aquifer that exists under flowing artesian conditions can have significant environmental and socio-economic consequences. Unfortunately**,** the risk of drilling a flowing well in different regions of British Columbia is largely unknown. This study used Multi-Criteria Analysis and the Analytical Hierarchy Process to map the likelihood of flowing well occurrence in three hydrogeologic contexts based on aquifer type and location; 1) Okanagan Bedrock, 2) Okanagan Unconsolidated and 3) Fraser Valley Unconsolidated. A novel approach was used to determine the weights of each factor by using the Wilcoxon Rank Sum Test. Each map was determined to reasonably display and predict the extent of flowing artesian conditions by using the Wilcoxon Rank Sum Test to a significance level of 15%. Through site specific evaluations, Well Drilling Advisories are recommended to be developed by the Province for Naramata, Armstrong, and Aquifer 33 in Langley to alert drillers of flowing artesian conditions.

Keywords: Artesian aquifers; flowing wells; flowing artesian wells; Okanagan; Fraser Valley; Multi-Criteria Analysis

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Chapter 1. Introduction

1.1. Introduction

Drilling into an aquifer that exists under flowing artesian conditions can unexpectedly add additional costs to drilling, in the range of thousands to millions of dollars (Lee, 2016). This is an issue for water well drillers and their clients, as well as geotechnical, environmental and geoexchange drillers who are required to stop or control artesian flow under the *Water Sustainability Act* (WSA). Additionally, wells that are allowed to flow uncontrollably have the potential to deplete the water supply in the aquifer (Province of BC, n.d.; Salameh & Tarawneh, 2017), and thus need to be considered in measures surrounding the management of groundwater supply. Therefore, flowing wells can have important socio-economic and environmental consequences.

In 2016, the province of British Columbia (BC) enacted the *Water Sustainability Act* (WSA), which contains requirements for controlling artesian flow from wells in BC. The WSA addresses controlling artesian flow during construction of new wells and of existing wells (Section 52 and Section 53) and drilling of wells that encounter artesian flow are now required to be reported (Section 57((3) (b))). Identifying areas where there is a higher likelihood of flowing wells is crucial for mitigating their risk.

The proposed research aims at improving the understanding of the factors that control the occurrence of flowing wells, and ultimately mapping the likelihood of flowing wells in three hydrogeologic contexts across two physiographic regions of BC:

1) Bedrock in the Okanagan Basin
2) Unconsolidated materials in the Okanagan Basin
3) Unconsolidated materials in the Fraser Valley

These two physiographically different areas will provide insight into conditions that result in flowing wells within low relief (Fraser Valley) and mountainous (Okanagan Basin) terrains. Further detail of these study areas is provided in Chapter 2.

1.2. Background

1.2.1. The Nomenclature of Flowing Wells and Flowing 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. Technically, 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 ground surface. Whereas in a *flowing artesian* well, the height of the water column is above the top of the ground surface and thus results in water discharging from the well (assuming the potentiometric surface is also above the well casing). 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 ground surface elevation. If 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 well top of casing because if the hydraulic head is below the top of casing it will not visually appear to be flowing.

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. Throughout this thesis, the term ‘flowing well’ is used to describe any well that is flowing regardless of whether the aquifer is confined or not. The term ‘under flowing artesian conditions’ is used when considering the aquifer.

1.2.2. Conceptual Models for Flowing Conditions

There are two widely accepted models of hydrogeologic environments that can result in flowing wells: geologically controlled models and topography controlled models (Freeze and Cherry, 1979). The term ‘artesian’ is technically only applicable to the geologically controlled model, although it is also used in the literature to refer to flowing

conditions in topography controlled conditions (e.g. Wang et al., 2015). These two models are discussed below.

Geologically Controlled Models

Geologically controlled flowing artesian conditions are associated with confined aquifers with several additional specifications. 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, and Fuller (1908) added a more robust consideration of their controlling factors.

Chamberlin (1885) initially identified seven requisites for the occurrence of artesian conditions and therefore flowing wells:

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 rain-fall precipitation to furnish this supply.
7. An absence of any escape for the water at a lower level than the surface at the well. (Chamberlin, 1885).

These conditions define a typical sloping confined aquifer which creates flowing artesian conditions in the down-dip region of the aquifer (Figure 1.1) Figure 1.1a shows a conceptual model with the potentiometric surface above ground surface at the location of the flowing well. Here, 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 unconfined), and the local elevation of the ground surface at the well. Figure 1.1b shows the arrangement of relative equipotential lines down the slope within the confined aquifer system. Within the zone “Flowing Artesian” delineated in Figure 1b, the deviation of the equipotential lines due to the difference in hydraulic conductivity between the confined aquifer and the confining layers results in the hydraulic head in the well being above ground surface.

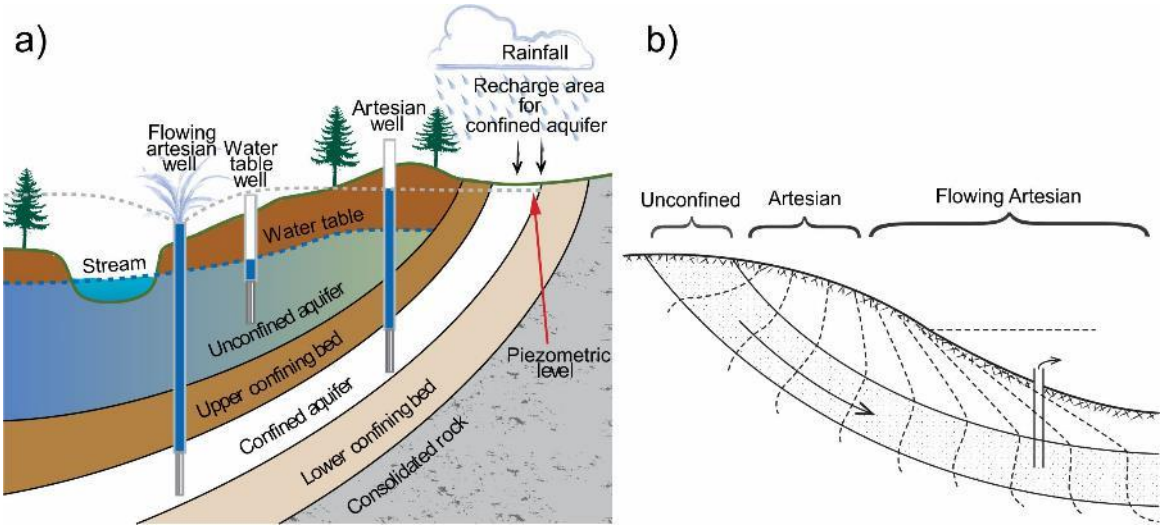

Figure 1.1 Geologically controlled artesian conditions which result in flowing wells. a) displays the potentiometric surface of the confined aquifer (source: Province of British Columbia, n.d.) b) displays the equipotential lines in the aquifer and the confining unit (Source: creative commons Freeze & Cherry, 1979).

The requisites outlined above are specific to geologically controlled artesian conditions. This is because the first three requisites simply reflect the definition of a confined aquifer, where (1) is the aquifer, and (2) and (3) are the confining units. It is 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 their occurrence is much less likely (Chamberlin, 1885). Requisites (3) to (6) describe the conditions necessary for creating a hydraulic head that is greater than ground surface, such that flowing artesian conditions would occur. The inclined beds create the conditions necessary for the hydraulic head in the aquifer to be above ground

surface, if the well is situated sufficiently down slope. Requisites (5) and (7) address the conditions necessary to create a sufficiently low gradient of water in the aquifer to allow the potentiometric surface to be above the ground surface to create flowing artesian conditions. Practically, this means that the topographic gradient must exceed the hydraulic gradient such that at some point down-gradient the groundwater level is above ground surface.

Topography Controlled Models

While geological conditions are generally better known as controlling conditions for flowing wells, Freeze and Cherry (1979) assert that topography is the primary control, as the conditions that create geologically controlled artesian conditions are not particularly common. Topographic relief is the reason for the common occurrence of flowing artesian conditions in valleys.

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. Topography controlled flowing wells can essentially occur anywhere that the groundwater flow direction is upward (i.e. where the hydraulic head is higher at depth than it is nearer to surface) such that the vertical gradient is sufficiently high for the head at depth (where the well is completed) to be higher than the ground elevation. Because of this, the flowing conditions are not extensive throughout the whole aquifer, but rather are more focused in topographic depressions where groundwater discharge occurs, such as the valleys bottoms. Figure 1.2 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.

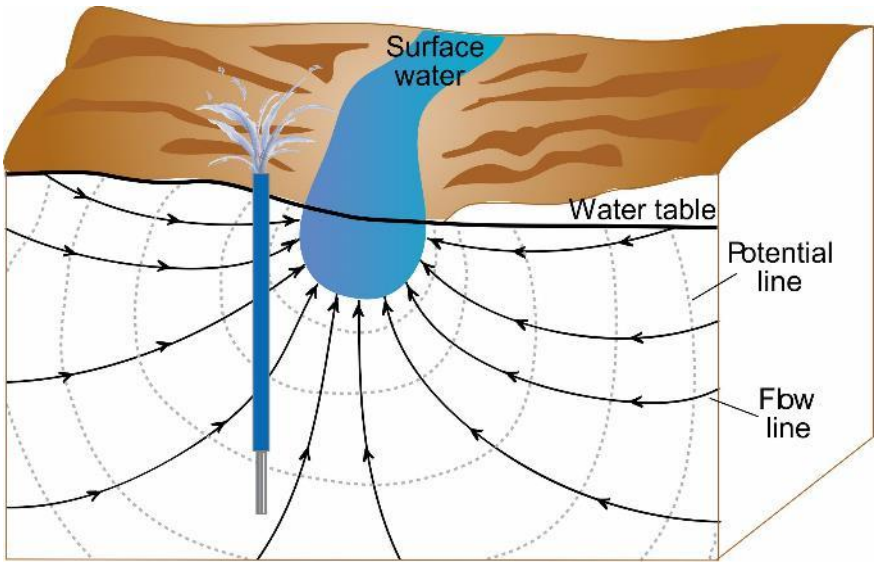

Figure 1.2 Flowing artesian conditions in topography controlled unconfined aquifer (Source: Province of British Columbia, n.d.)

1.2.3. The Models as End Members on a Spectrum

Fuller (1908) found the requisites determined by Chamberlin (1885) to be too limiting, and thus provided a more in-depth look at the controlling and modifying factors of flowing wells. He gave a more expansive consideration on what can be considered the water reservoir. While Chamberlin (1885) focused primarily on porous or fissured and channelled beds, Fuller (1908) went much more in-depth, giving multitudes of examples, such as vein contacts, cleavage planes, foliation, schistosity planes, etc. Fuller (1908) redefined the requisites for artesian flow, thus modifying the list of requisites made by Chamberlin (1885). The resulting essential requirements for artesian flow are much broader and are defined as:

1. An adequate source of water supply;
2. A retaining agent offering more resistance to the passage of water than the well or other opening; and
3. An adequate source of pressure. (Fuller, 1908)

The geologically and topography controlled models are defined by the source of pressure that results in flowing wells (the third essential requirement as defined by Fuller). In the geologically controlled model it is the sloping confined aquifer creating artesian pressure that results in flowing wells. Whereas in the topography controlled model, it is the topographic relief creating upward vertical gradients in discharge zones

that subsequently generates the pressure/upward gradient which results in flowing wells. These models are represented as being mutually exclusive in the literature.

Conditions which result in flowing wells are found where there is an upward vertical gradient within the aquifer (topography controlled) or aquifer-confining layer sequence (geology controlled). The two conceptual models are defined by the main drivers of this vertical gradient, where groundwater flow is controlled either by the geologic strata (i.e. geologically controlled) or the topography (i.e. topography controlled). However, these distinct models do not necessarily represent all occurrences of flowing artesian conditions. It is likely that these models represent end members of a spectrum of controls on flowing artesian conditions. For example, Toth (1963) developed a conceptual model of a confined aquifer in a sloping basin, which reflects the topographic control on the groundwater flow within confined aquifers (Figure 1.3). Toth (1963) did not develop Figure 1.3 as a case for flowing artesian conditions in a groundwater system, but nonetheless the figure depicts a deep sloping confined aquifer (similar to the geologically controlled model) where the groundwater exits the confined system and discharges in the topographic low (similar to a topography controlled model). Therefore, the presence of a confining unit does not necessarily signify that the flowing artesian conditions are determined solely by the geologic strata, and neither are flowing artesian conditions determined solely by the topography, but rather that the conceptual models represent end members of a spectrum. Generally, if a flowing artesian well is screened in a confined aquifer, the flowing conditions are deemed artesian and topographic effects are neglected.

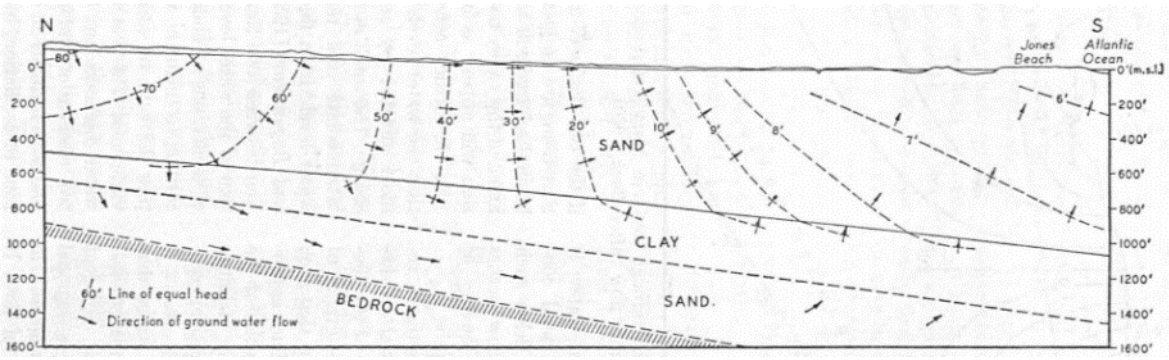

Figure 1.3 Effects of topography controlled groundwater movement in a confined aquifer (Source: Toth, 1963; Note: copyright permission granted from John Wiley and Sons).

Potentially, one real world example of where the current models are better understood as end members of a spectrum is a study in the Daly basin by the Northern Territory Government in Australia (Tickell, 2013). That study examined flowing wells within two main aquifers, the Tindall and Jinduckin aquifers, both of which are defined as mostly confined aquifers. No cross sections or stratigraphic information are provided to indicate whether these aquifers are planar or sloping (i.e. geologically controlled), but as confined aquifers it can be assumed that the aquifers are under artesian pressure. The author states, “topography is the main factor controlling the shape of the artesian area” (Tickell, 2013). In this case, it is likely that both the geology and topography are determining factors in creating the necessary pressure for flowing artesian conditions. This is just one example highlighting why the current system of categorising artesian aquifers is not equipped to identify all artesian conditions, and why the categorisation system may require redefining.

The conditions listed above are the only factors that Fuller (1908) defined as essential for creating artesian flow; they do not inherently indicate geological or topography controls. However, Fuller noted several other factors that contribute to artesian conditions in different ways, which he referred to as ‘modifying factors’:

Hydrostatic factors (relating to fluid pressure and movement)

1. Factors mainly affecting fluid pressure
    a. Barometric pressure
    b. Temperature
    c. Density
    d. Rock pressure
2. Factors mainly affecting fluid movement
    a. Porosity
    b. Size of pores or openings
    c. Temperature

Geologic factors (relating to reservoir)

1. Character of reservoir
2. Retaining agents
3. Structure of reservoir
4. Topographic conditions
5. Conditions relating to supply
    a. Catchment conditions
    b. Condition of underground feed
6. Conditions of leakage. (Fuller 1908)

The wide range of models presented by Fuller (1908) indicates a potential need for a new way of classifying artesian conditions. Based on the above requirements, it is clear the Fuller (1908) did not define artesian aquifers with a primary focus on geological conditions as did Chamberlin, nor did Fuller consider only topography controlled artesian conditions. The majority of the artesian aquifers that Fuller (1908) outlined at the end of his paper are geologically controlled, but not in the way described by Chamberlin (1885). Fuller gave a more expansive consideration of which hydrogeologic conditions could result in flowing artesian conditions. For example, Fuller considered unconfined aquifers where a flowing well is situated adjacent to a discharge zone of an aquifer (as illustrated in Figure 1.2). This demonstrates the versatility of Fuller's simpler essential conditions as his definitions of the controlling factors are not limited to either of the conceptual models and may indicate that a non-binary method of classification is necessary. Understanding the models that lead to flowing artesian conditions as a spectrum with two end members rather than two distinct models could aid in interpreting the extent of flowing artesian conditions and the factors that influence where/why flowing artesian conditions exist.

1.2.4. Modelling and Mapping of Flowing Artesian Conditions

Two main methods are used for determining the extent of flowing artesian conditions. The first is simply mapping the known occurrence of flowing artesian conditions (here defined 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 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 the well would be screened in. Jurisdictions that use occurrence mapping typically provide the data through a geographic information system (GIS) open data source (usually ArcGIS). Several jurisdictions were examined in regard to how they map flowing artesian conditions.

British Columbia

British Columbia (BC) has conducted both of occurrence and limited potential mapping of artesian conditions. Occurrence mapping uses water well information in the

provincial GWELLS database that can be accessed through iMapBC. Specifically, iMapBC includes a provincial data layer of known flowing artesian wells. The Vancouver drilling advisory (Province of BC, 2017) shows an area of potential artesian flow based on four known flowing artesian wells. The area was mapped using VanMap (a GIS interface from ArcMap) which contains only the four wells. Advisories have been published by the Province for Vernon Creek (Province of British Columbia, 2018d), Coldstream (Province of British Columbia, 2018a), Westwold (Province of British Columbia, 2018e), Surrey and Langley (Province of British Columbia, 2018b), Lower Mission Creek area of Kelowna (Province of British Columbia, 2017b), Vancouver, Burnaby and New Westminster (Province of British Columbia, 2018c), and Chetwynd (Province of British Columbia, 2017a).

Michigan

Michigan has an occurrence mapping system that is publicly available. Michigan's well database (Wellogic), maintained by Michigan's Department of Environmental Quality, contains data specific to artesian wells. Michigan also conducted the Michigan Groundwater Inventory and Mapping Project; artesian aquifers were not specifically mapped in the project, but wells in 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 because 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 many decades due to increasing population, and this increase in groundwater use could have 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 to 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 artesian flow but are not currently being used in that way.

Parts of Florida have been modelled (and therefore partially mapped for flowing artesian conditions). One such model was developed for the east coast of the Floridan Aquifer System (FAS) (Golder Associates Inc., 2008). The Upper Floridan Aquifer exists under flowing artesian conditions (throughout the modelled area), with the exception of the area north of Lake Okeechobee, in Southern Florida District where the potentiometric surface remains below ground level (Golder Associates Inc., 2008, pg. 23). This model's purpose was not to predict or infer artesian flow specifically; rather it included a mapping component that was specific for artesian conditions in the aquifer. The modelling project defined multiple potentiometric surface maps for both the Upper Floridan Aquifer and the Lower Floridan Aquifer (which together define the FAS). The three models that were developed/calibrated for this project used SEAWAT 2000 (Langevin et al., 2003). There are also several other modelling projects of this type in other regions of Florida.

1.3. Mapping Flowing Artesian Conditions and Multi-Criteria Analysis

While occurrence mapping and predictive mapping are the most common methods for identifying where flowing artesian conditions might exist, other mapping techniques can potentially be used. Multi-criteria analysis (MCA) is one such method. It is important to note that MCA is also referred to as Multi-Criteria Decision Analysis (MCDA) or Multi-Criteria Decision Making (MCDM). Despite the latter terms being more common, this thesis uses the term MCA because there is no 'decision' being made in the MCA application.

1.3.1. Multi-Criteria Analysis

Multi-Criteria Analysis (MCA) was originally developed as a decision making tool to be able to evaluate problems that have a multitude of criteria, which are ranked based on their relative importance. The analysis uses a weighted linear equation to evaluate the criteria for each decision or factor (Malczewski & Rinner, 2015). MCA was not initially

a GIS method but was adapted for GIS over time. A classics example (non-GIS) of a problem for which MCA can be used is hiring decisions. There are four main elements for a MCA (Malczewski & Rinner, 2015):

1. Decision Alternatives: the alterative courses of actions that can be taken that can be chosen by the decision maker.

2. Criteria: The criteria (attribute and objectives) used to evaluate the decision alternatives.

3. Weights/Decision Matrix: The ranking of the relative importance of each criterion to each other criterion.

4. Decision Makers: People whose preferences are represented, usually through the weighting of the criteria.

For the hiring example, the decision alternatives are the candidates being considered for the job. The criteria could be represented by the desired qualities of each candidate (e.g. experience, education, etc.). The weights are determined by which criteria are perceived by the decision makers to be the most important. Lastly, the decision makers would be the future employers.

There are multiple common techniques used to perform MCAs. The Analytical Hierarchy Process (AHP) was developed by Saaty in the 1970s (Saaty, 1987) and is one of most popular techniques. AHP is used to determine the weights in the weighted linear equation; it is a pairwise comparison method which ranks the criteria against each other using their relative importance to determine the weights using a decision matrix (MCA element 3 above). The relative importance of each criterion is traditionally defined qualitatively.

1.3.2. Multi-Criteria Analysis in GIS for Mapping Likelihood

MCA has been widely adapted for use in a GIS and is even built into some GIS software (e.g. TerrSet). Combined with GIS, MCA can be used to map likelihood of an outcome. MCA can be applied in both raster and vector contexts[1]. In the raster context,

[1] Discussion is limited to the raster context as that is the method utilized in this thesis.

decision alternatives are no longer represented by the alterative courses of action, but rather are represented by the cells of a raster. The criteria can now represent spatial data sets, which represent different factors; for example, factors that might affect the occurrence of flowing artesian conditions. A weighted linear equation (Equation 1.1) is applied to each raster cell to produce a map where cells with higher values will indicate a higher likelihood of flowing artesian conditions. The preferences of decision makers/stakeholders are not applicable when determining the weights in this context.

$$Flowing\ Well\ Occurence = [(w_1 * f_{w1}) + (w_2 * f_{w2}) + \dots (w_n * f_{wn}) \qquad (1.1)$$

1.3.3. Advantages and Limitation of MCA

There are several advantages to using MCA and AHP.

1. Provide a systematic approach for the mapping the likelihood of an outcome. This allows the methodology to be easily replicated across study areas while being able to accommodate the differences deemed to be statistically significant between the study areas (i.e. different determining factors).

2. Allow for qualitative and quantitative factors to be used in the analyses. This allows for categorical data to be incorporated into the analysis.

3. Advantageous when there is no single factor that has a controlling effect on the likelihood.

There are also several general limitations to MCA as outlined by Thakkar (2021).:

1. Difficulty in structuring an appropriate hierarchy will lead to a faulty selection or prioritization of the alternatives.

2. Primarily governed by subjective opinions of the experts and their intuitions, and hence bias in the judgment and inconsistency limits the acceptability of MCA results.

3. Difficulty in validating the results with the alternate MCA technique as the key properties and steps followed by various MCA techniques are different. This limits the generalization of the results.

4. The criteria and alternatives are dynamic in nature for a real-life problem and hence the priorities or ranking generated by MCA technique may not remain valid for a longer-period time and hence it is advisable to support the results of MCA with a detailed sensitivity analysis. (Thakkar, 2021)

1.3.4. Previous Application of MCA to Groundwater Research

Since MCA's initial inception it has been applied extensively in a wide variety of fields including (but not limited to) engineering, science, humanities, social sciences, and policy (Thakkar, 2021). It has also been applied to various scenarios surrounding groundwater. Mapping groundwater potential is common use of MCA in groundwater resource application. Rubio-Alaga et. al (2021) applied the AHP and TOPSIS (another MCA technique) to select the optimal groundwater pumping systems. Arabameri et al. (2020) used a variety of artificial intelligence techniques to map groundwater potential in Iran. MCA techniques have also been applied to aid in groundwater management; for example, Roozbahani et al. (2018) used Bayesian networks to predict groundwater levels and MCDM techniques to evaluate groundwater management scenarios. Additionally, Guar et al. (2021) used VIKOR and TOPSIS techniques to evaluate 20 groundwater planning strategies.

To the author's knowledge, MCA has not been previously used to map flowing artesian conditions, but it has been applied in the context of mapping spring occurrence. Bystron (2018) used the AHP technique true to Saaty's original methodology to predict potential spring occurrence (both in Quaternary sediments and bedrock) in the Peace River Regional District of British Columbia. Bystron (2018) used Multi Criteria Decision Analysis (MCDA) to map the likelihood of occurrence of springs (both in Quaternary sediments and bedrock) in an area of the Peace Region. In the literature, springs and flowing wells share multiple factors which influence the occurrence of spring and flowing wells because of the influence that these factors can have on groundwater paths (Ozdemir, 2011; Al-Abadi & Ahahid, 2016).

1.4. Purpose and Research Objectives

The main purpose of this research is to determine the extent of flowing artesian conditions in two physiographically different study areas in British Columbia using a

systematic mapping method. In meeting this goal, a more comprehensive understanding of the controlling and determining factors for flowing artesian conditions will be achieved, particularly demonstrating how flowing artesian conditions can be both geologically controlled and topographically controlled.

The specific objectives of the research included:

1. Develop a method for mapping the likelihood of occurrence of flowing artesian conditions.

2. Test the mapping method in a variety of hydrogeologic contexts.

3. Validate the mapping results using quantitative (statistical) and qualitative (conceptual) methods.

4. Demonstrate the importance of considering factors that relate to geologically and topographically controlled models.

The Okanagan Basin and the Lower Fraser Valley in BC were chosen as the study areas for four main reasons: 1) they are physiographically different, representing mountainous and low relief terrain; respectively, 2) they represent two different hydrogeological contexts (bedrock and unconsolidated sediments); 3) they have the highest density of wells in the province; and 3) they have high numbers of flowing wells.

This project was funded by the Ministry of Forest, Lands, Natural Resource Operations and Rural Development through the BC Water Science Program.

1.5. Scope of Work

Objectives 1 and 2

1. Carry out occurrence mapping (presented in Chapter 2) of flowing wells in the two study areas (Okanagan and Lower Fraser Valley) using water well data from the provincial GWELLS database.
2. Engage with well drillers and professionals during the BC Groundwater Association (BCGWA) conventions (2019 and 2021) to glean practical

(geological) knowledge and the hydrogeological (groundwater) context surrounding known cases of flowing wells.

3. Within a GIS environment, assess factors (e.g. elevation, slope, and curvature) with a hypothetical control on flowing artesian conditions and determine if they are suitable for use in the MCA through statistical methods.

4. Map the likelihood of flowing wells in the Lower Fraser Valley and the Okanagan Basin. The likelihood maps will be developed in a GIS and will show areas where flowing wells are more likely than non-flowing wells to occur based on the percent frequency distributions.

Objectives 3 and 4

1. Develop conceptual hydrogeological models for the occurrence of flowing wells for specific locations within the three hydrogeologic contexts. This work will be carried out primarily in GIS in combination with LeapFrog Geo (Seequent, 2019) (for developing three-dimensional geological models in the unconsolidated contexts) and GMS (for developing a two dimensional model for the bedrock contexts).
2. Assess the current Well Drilling Advisories published by the Province of British Columbia for the two study areas and provide recommendations for modifications to current advisories and potential new advisories.

1.6. Organisation of Thesis

This thesis is organised into a series of chapters:

Chapter 1 – Introduction: Introduction to the thesis, literature review, purpose and objectives, and scope of work.

Chapter 2 – Study Sites: Including available information such as presented in the occurrence mapping, along with overviews of the geological history, geological units of significance, and hydrogeological relevance.

Chapter 3 – Data Processing: Detailed overview of the methodology and results from the data processing.

Chapter 4 – Multi-Criteria Analysis Maps: Results produced by the MCA mapping approach.

Chapter 5 – Case Studies: Site specific evaluations within the three hydrogeologic contexts.

Chapter 6 –Conclusions: Overview of the research limitations, conclusions and recommendations.

Chapter 2. Study Areas

2.1. Overview

In this thesis flowing artesian conditions are examined in three hydrogeologic contexts across two study areas 1) the Lower Fraser Valley and 2) The Okanagan Basin (Figure 2.1). The contexts are based on aquifer material 1) Bedrock and 2) Unconsolidated sediments. This chapter details the physiography of the study areas as well as the basic statistics of flowing artesian wells. The wells dataset is the GWELLS database and was downloaded in 2019 (Ministry of Environment and Climate Change Strategy, 2019).

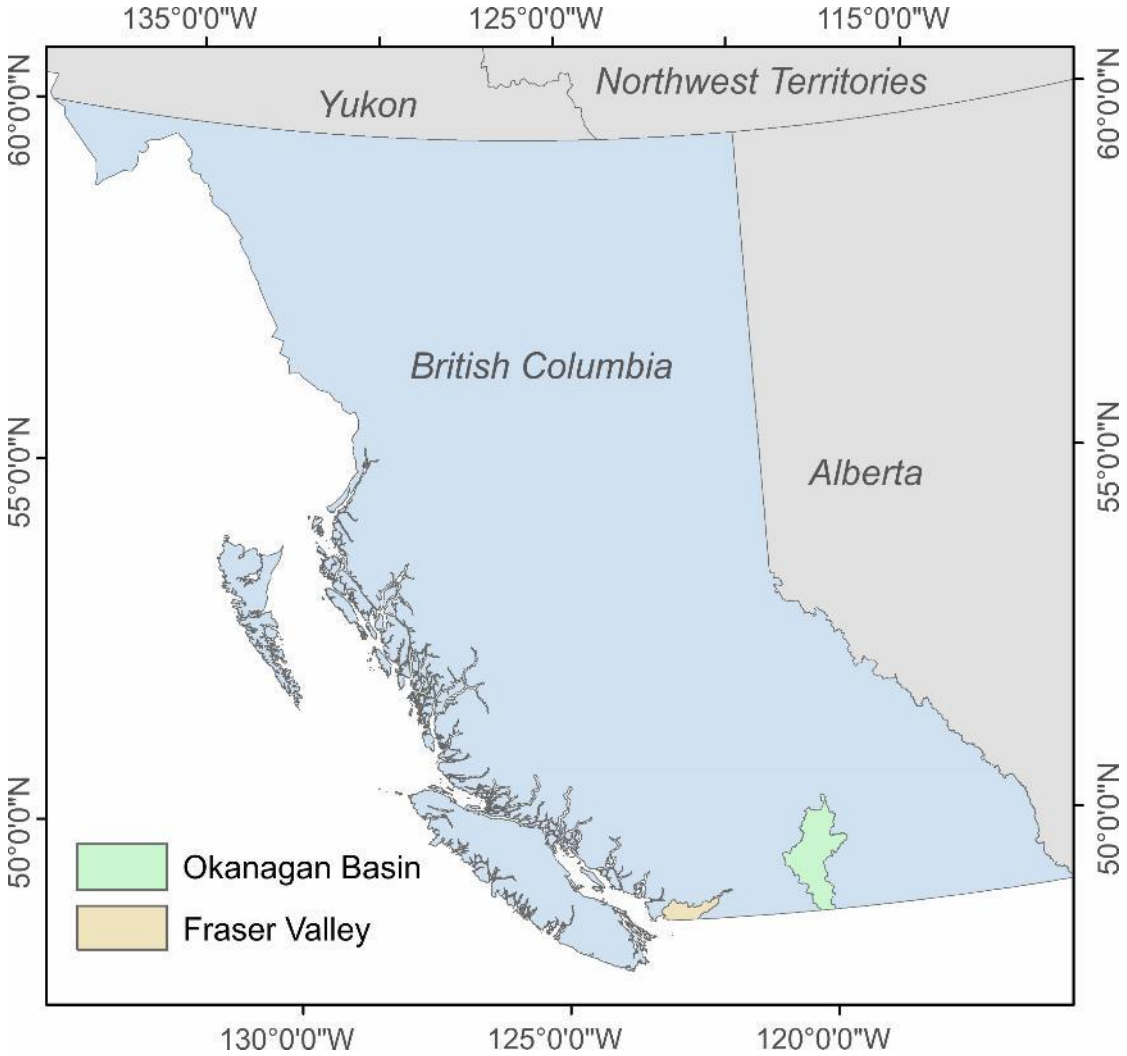

Figure 2.1 Location of the Fraser Valley (tan) and Okanagan Basin (green) in the Province of British Columbia (blue)

2.1.1. Okanagan Basin

The Okanagan Basin is located in south-central BC. The basin trends north-south, spanning from just north of the City of Armstrong to Osoyoos at the Canada-USA border. Within BC, the basin is 200 km in length and approximately 8000 km^2 in area (Figure 2.1). Okanagan Lake, extending throughout much of the valley bottom, is flanked with mountains on east and west with elevations ranging from 300 metres above sea level (masl) to 1800 masl. Population densities are higher in the valley bottom as is water well occurrence.

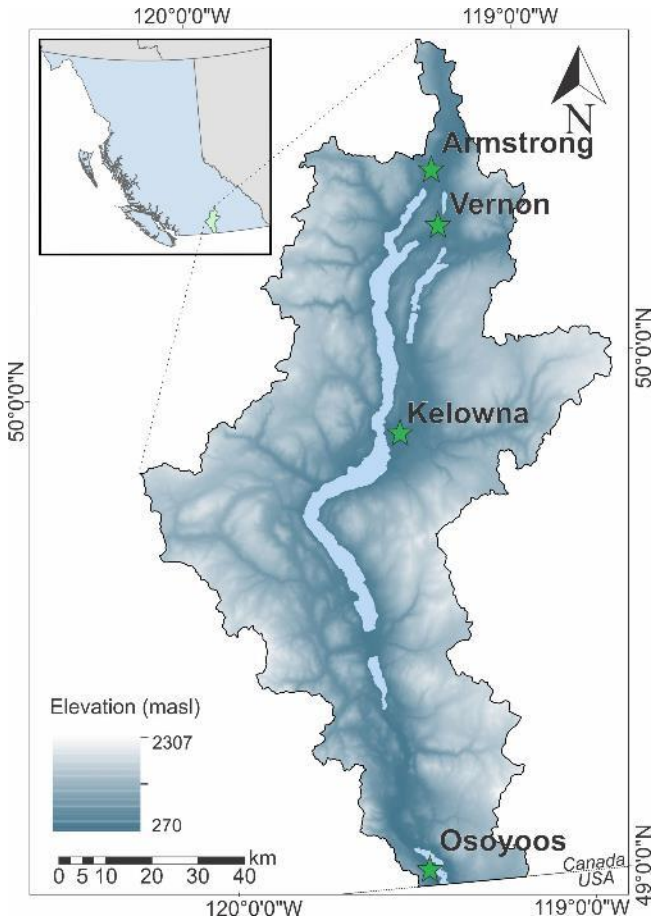

Figure 2.2 Digital Elevation Model of the Okanagan Basin with major cities identified.

The Okanagan Basin valley is filled with unconsolidated sediments and the underlying bedrock becomes exposed as elevation increases. The 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 characterised 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.

2.1.2. Fraser Valley

The Lower Fraser Valley (henceforth Fraser Valley) is located in southwest BC. The Fraser Valley has low to moderate relief with elevations generally ranging from ~sea level to 150 masl (Clague et al., 1983), with the high elevations representing the Fraser highlands and the edge of the Coast Mountains and the Cascade Mountains. One notable exception is Sumas Mountain, which has an elevation upwards of 800 masl. The study area (~1800 km^2) encompasses only the valley bottom (Figure 2.3) and extends from Hope in the west to the Salish Sea in the east, and from the Pacific Ranges of the Coast Mountains in the north to Canada-USA border and the Cascade Mountains to the south. It excludes the surrounding high elevation areas along the edges of the valley because they have low population densities and few to no wells drilled.

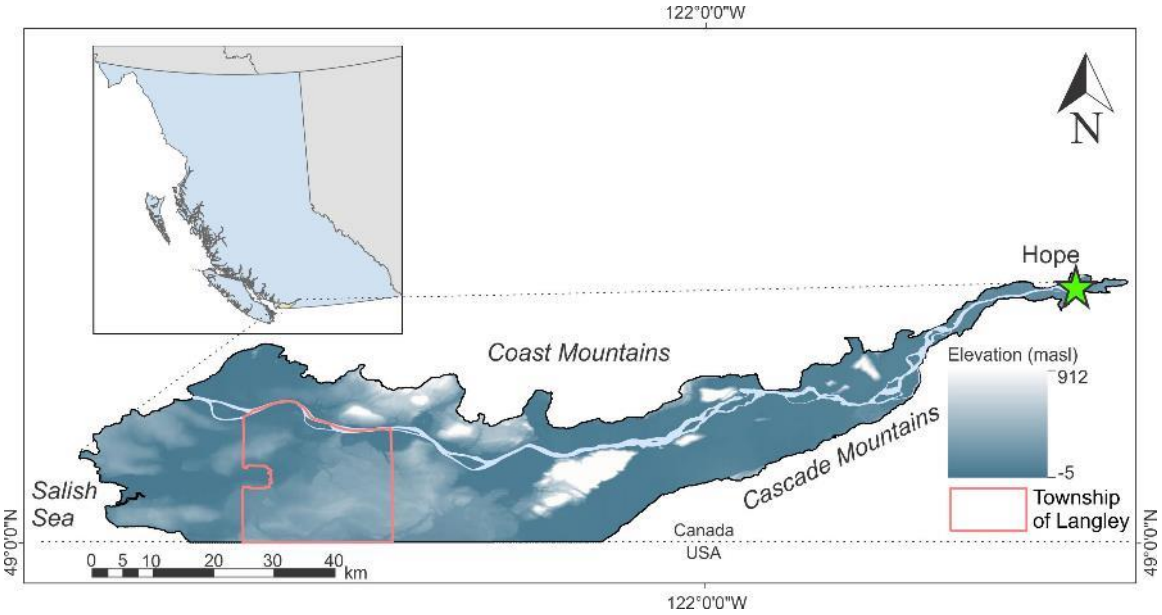

Figure 2.3 Digital Elevation Model of the Fraser Valley with the Township of Langley identified in red.

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 cut the glacial deposits throughout the Fraser Valley (Clague & 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).

2.2. Flowing Well Statistics

2.2.1. Okanagan

There are 7471 non-flowing wells reported in the Okanagan Basin and 533 flowing wells (Figure 2.4a). These numbers are likely underestimates due to the GWELLS database likely not containing every well. 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 are more heavily clustered in the central and northern Okanagan Basin. The Okanagan Basin has more clusters with fewer wells relative to the Fraser Valley which has only a few clusters (see Section 2.2.2), but those clusters contain the majority of the wells. 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.

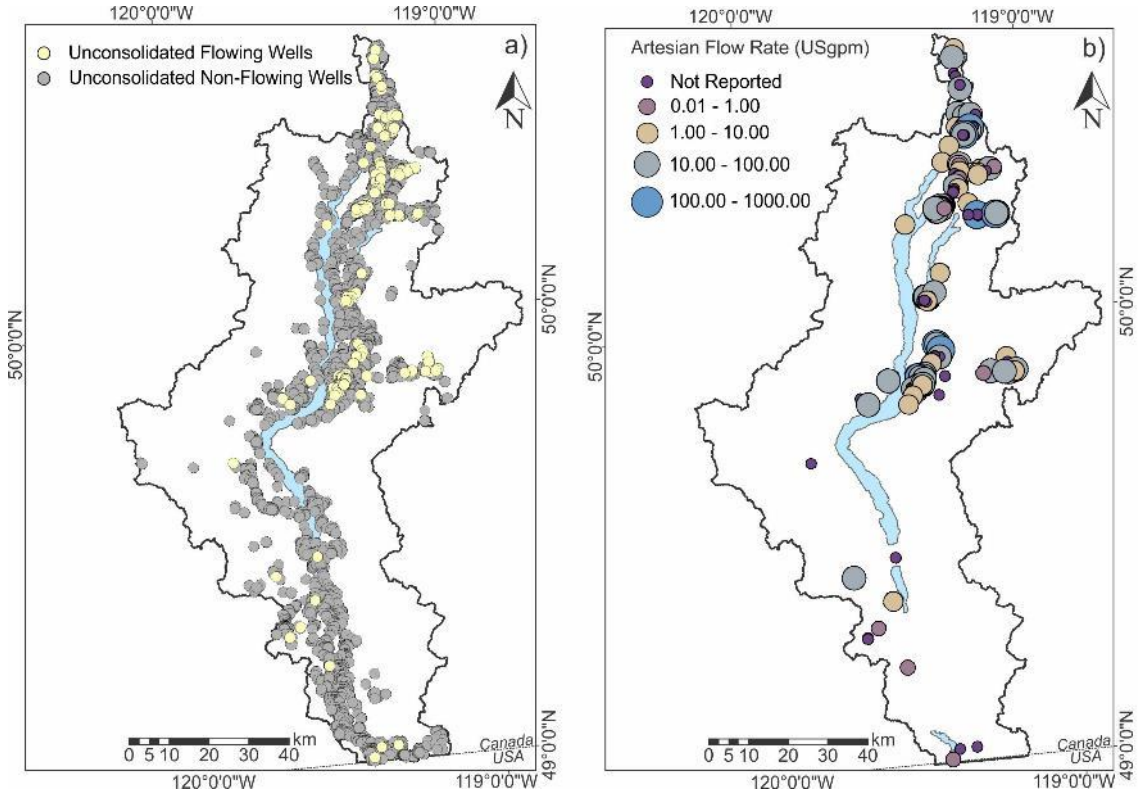

Figure 2.4 a) Flowing and non-flowing wells in the Okanagan Basin b) Flow rates of flowing wells reported in US gallons per minute (USgpm).

The reported flow rates range up to 600 US gallons per minute (USgpm) (Figure 2.4b; Table 2.1), although these flow rates have not been field verified. Wells without reported flow rates make up the largest category in Table 2.1 (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 2.5). 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.

Table 2.1 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

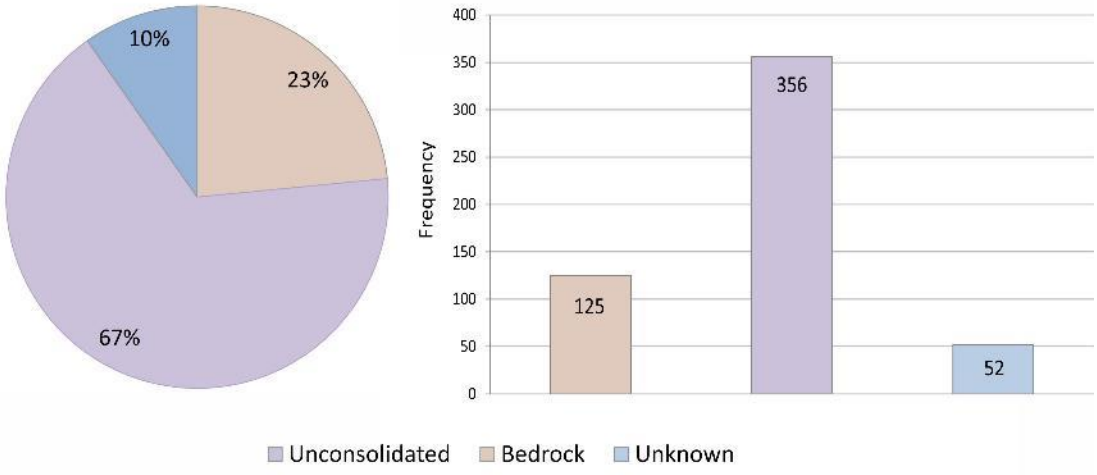

Figure 2.5 Aquifer Lithology for flowing wells in the Okanagan Basin in percent (pie graph) and frequency (bar graph)

2.2.2. Fraser Valley

There are 15,905 non-flowing wells reported in the Fraser Valley and 786 flowing wells (Figure 2.6a). 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 (see Figure 2.3) 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.

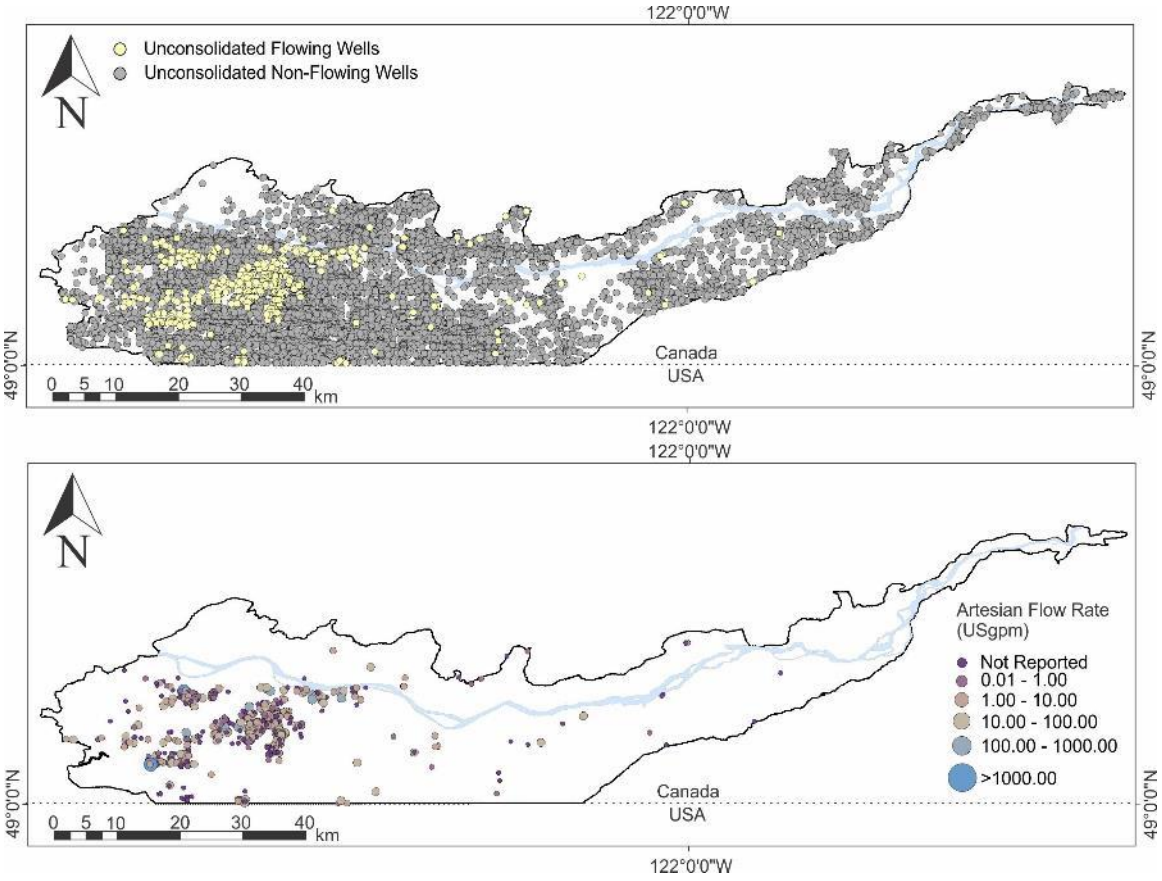

Figure 2.6 a) Flowing and non-flowing wells in the Fraser Valley b) Flow rates of flowing wells reported in US gallons per minute (USgpm).

The reported flow rates range up to 1800 USgpm (Figure 2.6b; Table 2.2). Flowing wells without reported flow rates have the highest frequency (341 wells; 43.4%) in Table 2.2. 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 2.7). 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.

Table 2.2 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

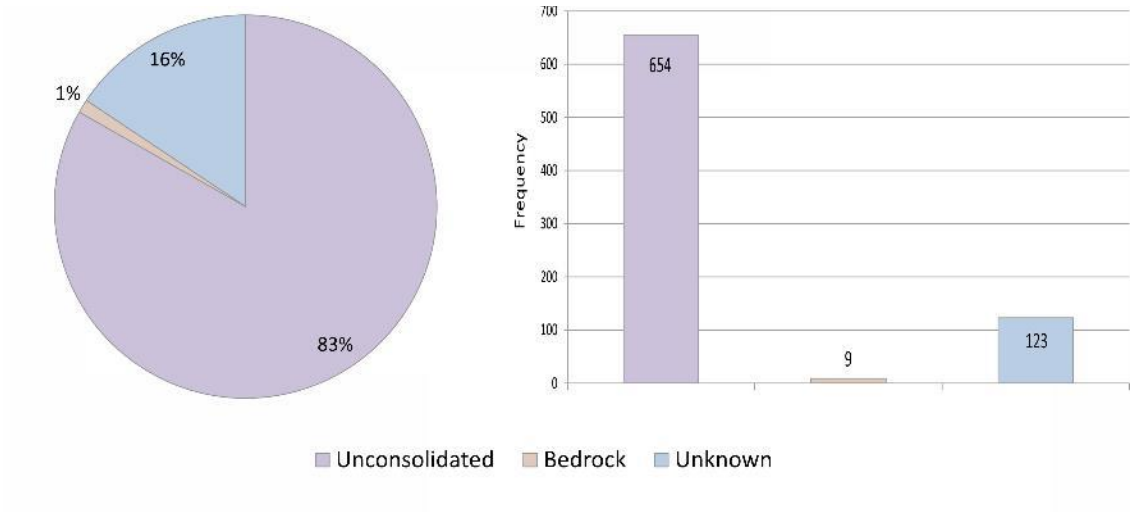

Figure 2.7 Aquifer Lithology for flowing wells in the Fraser Valley in percent (pie graph) and frequency (bar graph)

2.3. Drillers' Input (BCGWA Convention)

The BC Ground Water Association (BCGWA) convention was attended in 2019 and 2021 to engage with well drillers and professionals. In April of 2019, large format maps of each study area were prepared and displayed at the convention in Langley. A brief overview of the scope of the study was presented with the aim of encouraging drillers and other groundwater professionals to stop by the maps and identify the locations of flowing artesian wells that they were aware of, and to generally share their knowledge of flowing artesian wells in the province. The flowing wells mapped during this interactive display were not used for the data analysis due to the potential lack of

accuracy in the location; however, the well locations generally confirm the trends of data shown in the GWELLS database.

The annual BCGWA convention was held virtually in the spring of 2021. The preliminary results from the MCA mapping for the Okanagan Bedrock context were presented. The virtual platform allowed to convention participants to ‘sit’ at tables with each other, which allowed for some feedback to be gathered from the audience.

Chapter 3. Data Processing

3.1. 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; Guar et al. 2021; Rubio-Alaga et. al., 2021). When applied in a GIS context it 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 & Rinner, 2015). The results of the MCA analysis are displayed on a map. 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 equation that is applied to each raster cell in a series of steps outlined in Figure 3.1. The numbered components in Figure 3.1 indicate the steps for the construction of the MCA map, which are as follows:

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 (Figure 3.1).

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 (Figure 3.1).

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. Map validation - the resulting map is validated statistically by using a series of Wilcoxon Rank Sum Tests.

The subsections of this chapter describe the data processing methods used for each step of Figure 3.1 in more detail (Section 3.2 – Section 3.5). The final MCA maps along with the final step (Map Validation) are presented and discussed in Chapter 4.

Three hydrogeological contexts were studied: 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. Throughout this chapter the Okanagan is used as an example. The full-size maps for the Okanagan and all maps for the Fraser Valley can be found in Appendix A.

ESRI ArcMap 10.6 was used for the spatial data analysis and integration, and MATLAB R2018a was used to perform the statistical analyses.

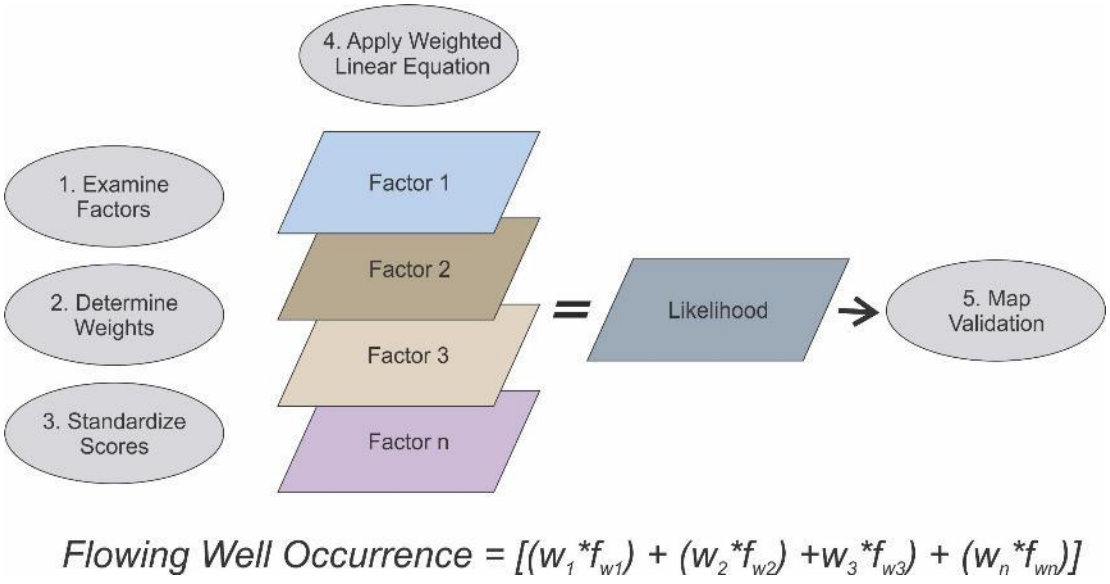

Figure 3.1 Overall stepwise approach for the Multi-Criteria Analyses. Steps 1 – 4 are detailed in subsequent sections of this chapter. Step 5 is detailed in Chapter 4.

3.2. Examination of Factors

3.2.1. 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 3.1 lists these potential factors, along with the data source

used in the analysis. These factors were selected for examination based on previous studies described in Chapter 1.

Table 3.1 Factors considered for MCA.

Factor	Data File	Source
Elevation	BC Digital Elevation Model	GeoBC
Slope		
Curvature		
Flow Accumulation		
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

Factors were selected 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 & 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. Figure 3.2 displays the workflow for data processing. The blue diamonds represent unprocessed spatial data (i.e. data files from Table 3.1) that were used to derive the factors evaluated for the 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 3.2.2. 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.

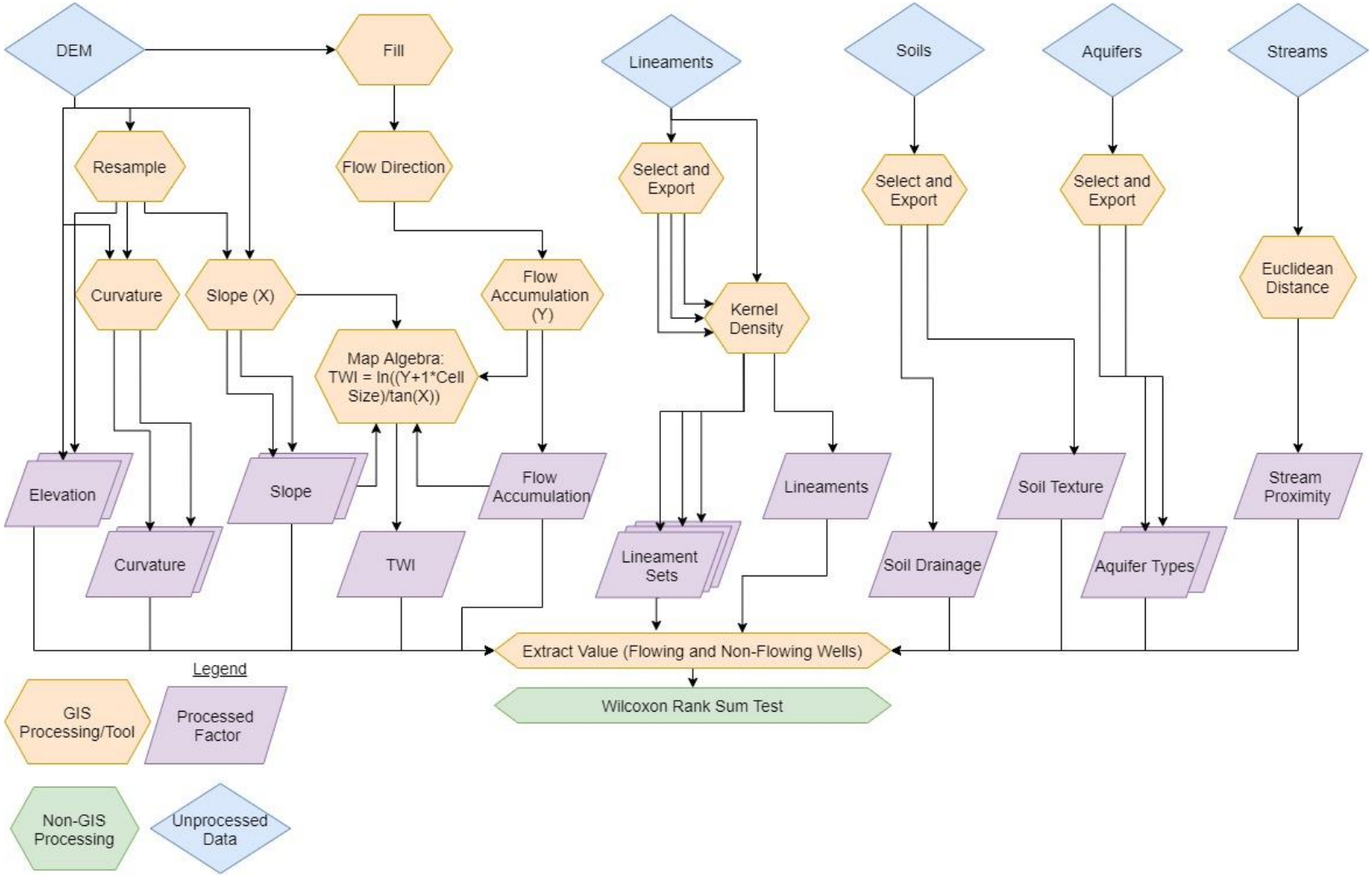

Figure 3.2 Workflow for data processing all factors.

DEM and DEM Derived Factors

Elevation, slope, curvature, flow accumulation, and Topographic Wetness Index (TWI) were derived (or taken directly) from the digital elevation model (DEM). The DEM was sourced from DataBC (BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2012) and has a cell size of 20.5 m x 20.5 m.

The occurrence of flowing artesian conditions requires the hydraulic head in the well to be above ground level. As described in Chapter 1, 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.

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, as well as spring occurrence (Ozdemir 2011; Al-Abadi & Shahid 2016; 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 presented in Figure 3.3a.

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 and spring occurrence (Ozdemir 2011; Al-Abadi & Shahid 2016; Bystron, 2018). Similar to elevation, slope is considered for all three hydrogeological contexts. The slope raster for the Okanagan Bedrock is presented in Figure 3.3b.

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). A flat surface is represented by a curvature value of 0, 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 and spring occurrence (Ozdemir 2011; Al-Abadi & Shahid 2016; Bystron, 2018). Curvature was evaluated for all hydrogeological contexts. The curvature raster for the Okanagan Bedrock is presented in Figure3.3c.

Elevation, slope and curvature were computed in ArcMap using the GIS Tools of the same names (Figure 3.2). 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 (Figure3.3a) and slope (Figure3.3b) used the original grid size, while curvature (Figure 3.3c) 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 3.3c 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

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 that would flow into that cell. 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 to occur where the subsurface flow contribution area is large.

Flow accumulation is calculated through a series of steps in ArcMap using the GIS tool of the same name (Figure 3.2). 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 3.4a).

Topographic Wetness Index

Topographic Wetness Index (TWI) is a steady state wetness index that uses the calculated slope and flow accumulation (Equation 3.1; 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.

$$TWI = \ln\left(\frac{SCA}{tan\varphi}\right) \tag{3.1}$$

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 3.4b). 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.

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 3.2 (Beven & Kirby 2009).

$$TWI = \ln\left(\frac{Y * Cell\ Size}{tan\left(X * \left(\frac{\pi}{180}\right)\right)}\right) \quad (3.2)$$

where:
Y = flow accumulation
X = slope
Cell size = 20.5 m.

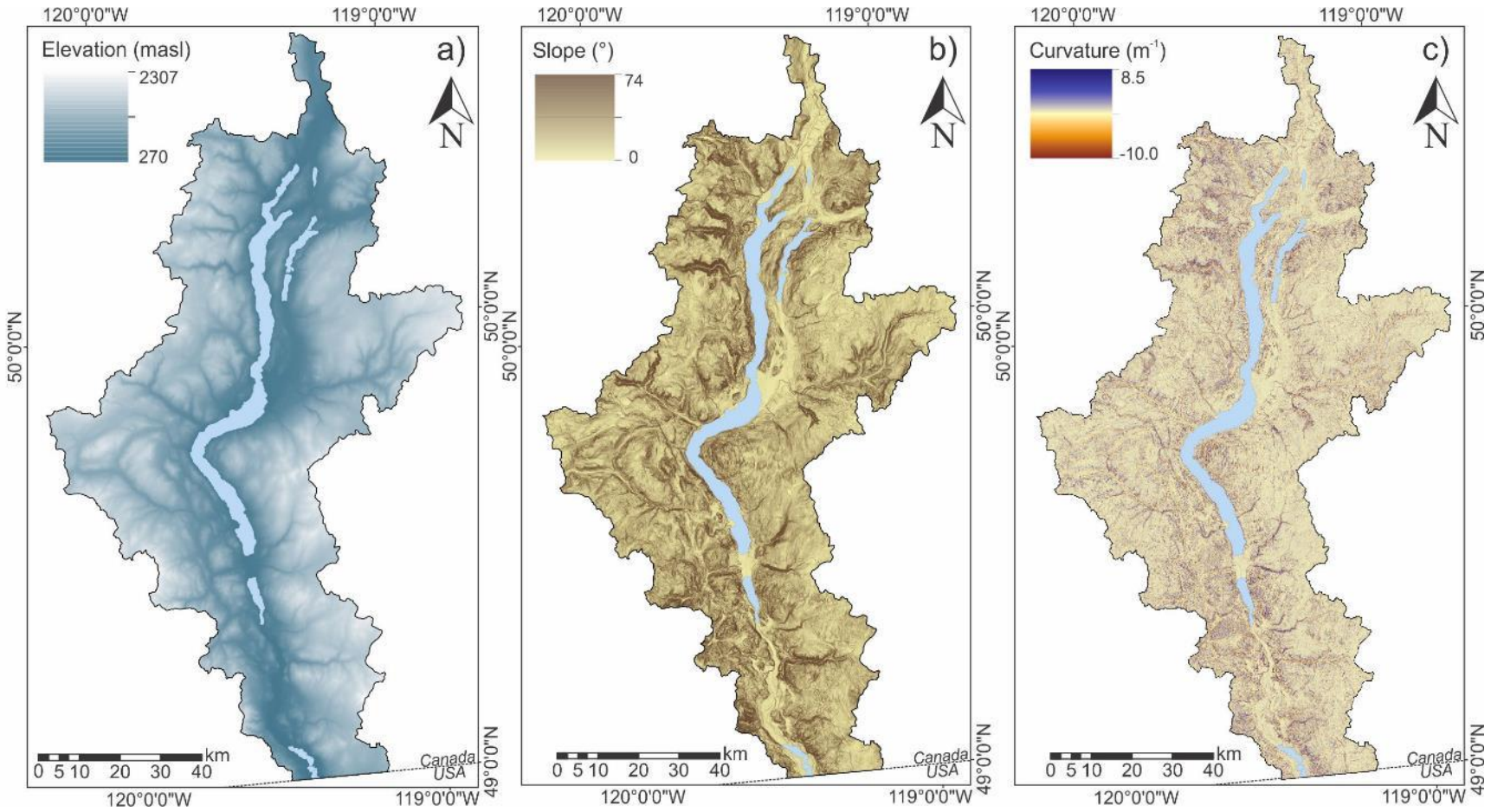

Figure 3.3 Okanagan factors derived from the DEM a) Elevation b) Slope c) Curvature.

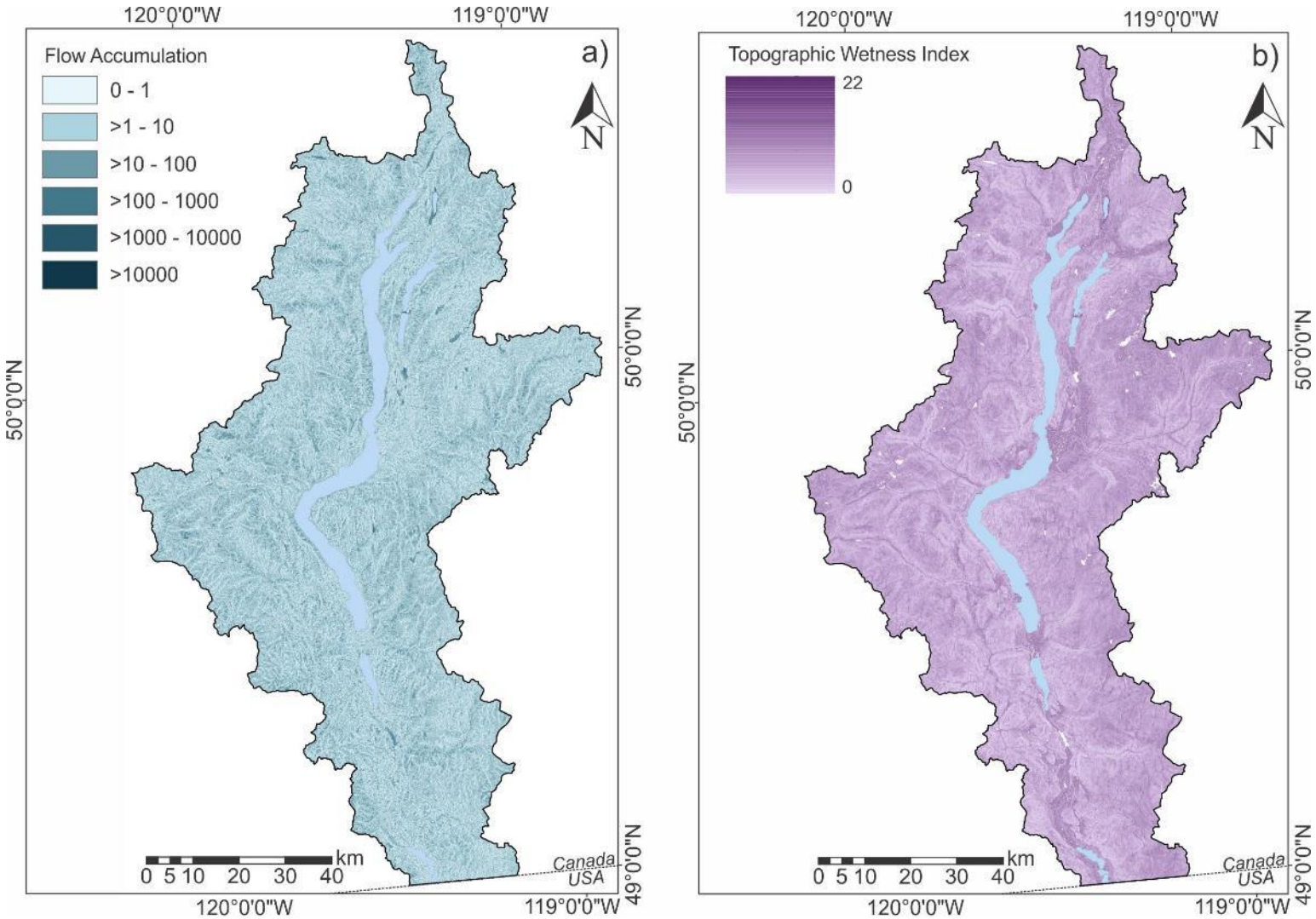

Figure 3.4 Okanagan factors derived from the DEM a) Flow Accumulation b) Topographic Wetness Index.

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 & 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 3.5a). 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.

In this study, kernel density maps of the lineaments were produced in ArcMap (Figure 3.5b), following a similar approach by Voeckler & 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). 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).

Voeckler & Allen (2012) associated the lineaments with three sub-vertical fracture sets mapped in outcrop; one sub-horizontal fracture set mapped in outcrop could not be

associated with the lineaments. Lineaments that are daylighting on the surface tend to have a bias towards steeply dipping fractures and faults. This is because the more horizontal features are not as visible and are less likely to daylight. In this study, the lineament data were categorised into these three fracture sets based on the lineament strike direction (Figure 3.5c). Sets 1 and 2 have similar strike ranges and are distinguished based on the dip direction measured in outcrop (Voeckler & Allen, 2012). For this study, these two sets were grouped together as a single set as differences in dip direction cannot be accounted for in a two-dimensional GIS environment (Table 3.2). The same Kernel Density analysis was conducted on each strike lineament set (Figure 3.6).

Table 3.2 Lineament sets used for the kernel density analysis and the original lineament sets from Voeckler & Allen (2012) from which the new sets were derived.

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

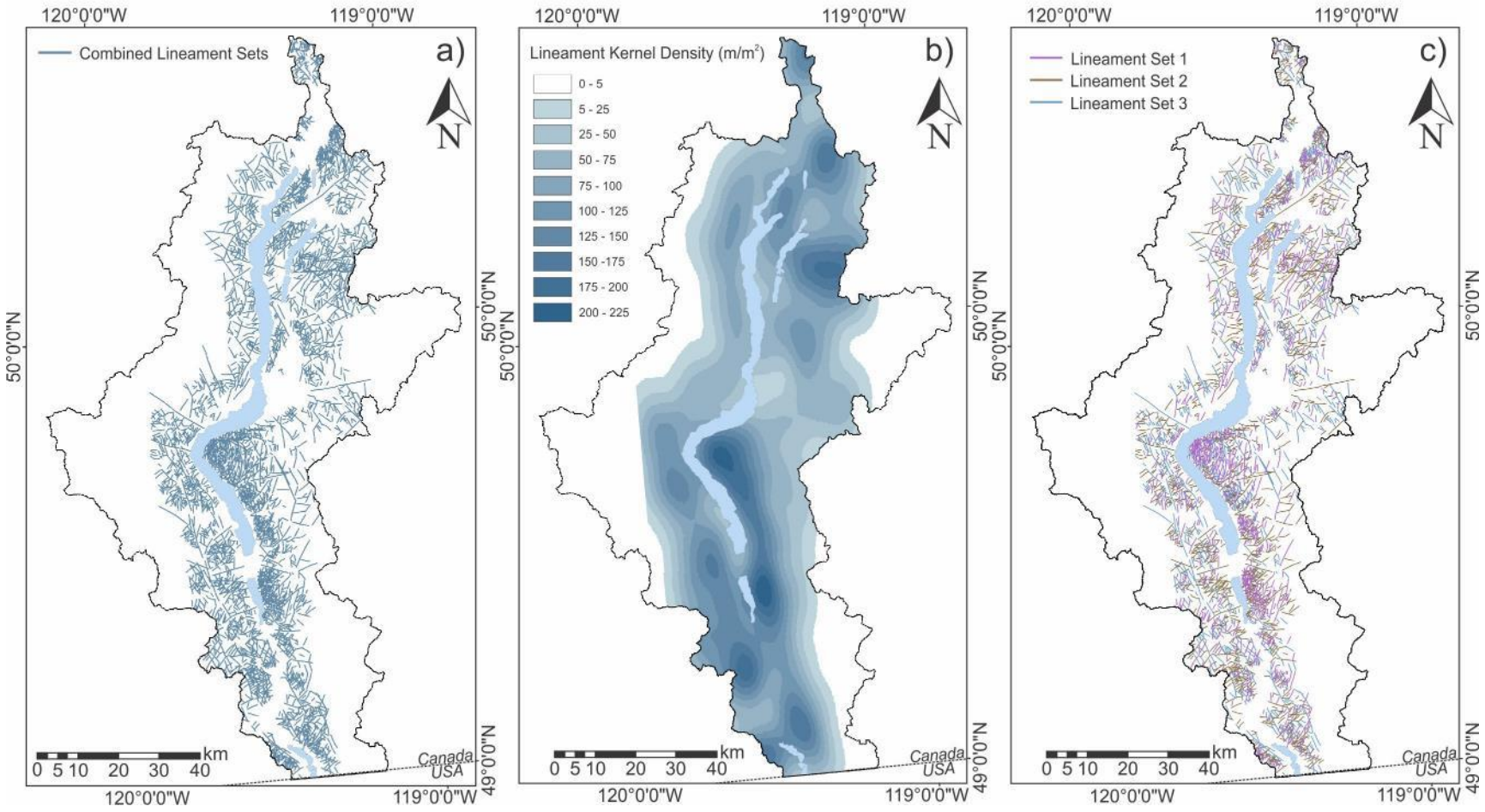

Figure 3.5 a) Combined lineaments in the Okanagan b) Lineament kernel density map for the combined sets c) Three lineament sets in the Okanagan classified based on Voeckler & Allen (2012) (Table 3.2).

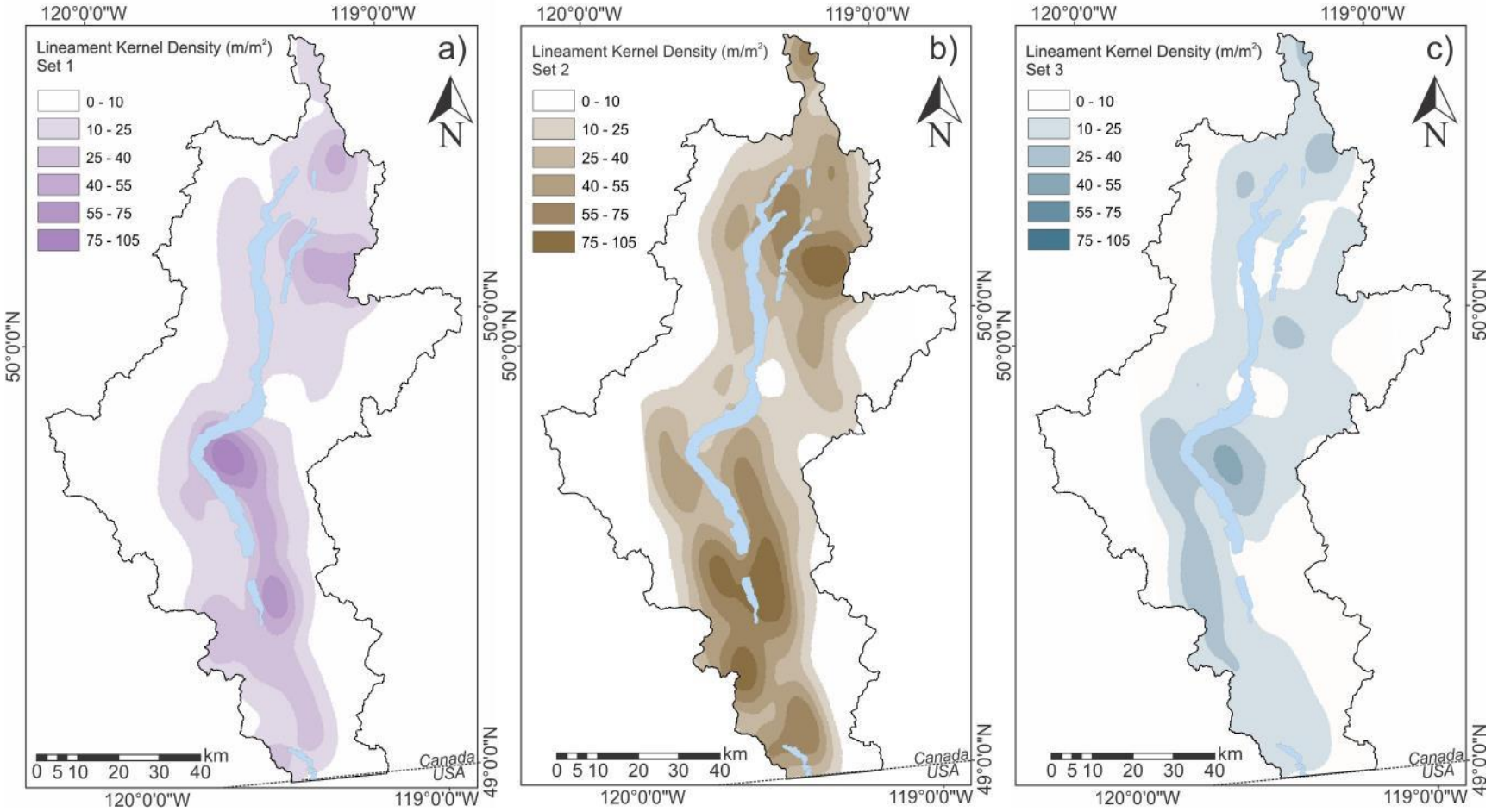

Figure 3.6 Lineament kernel density maps for a) Set 1 b) Set 2 c) Set 3.

Soil

Two soil related factors were considered for the MCA: soil drainage and soil texture (Figure 3.8). 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. 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.

Soil texture polygons (Figure 3.8a) and soil drainage polygons (Figure 3.8b) were obtained from the BC Soil Information Finder Tool (SIFT) (BC 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 3.7) and drainage as described in Table 3.3. 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.

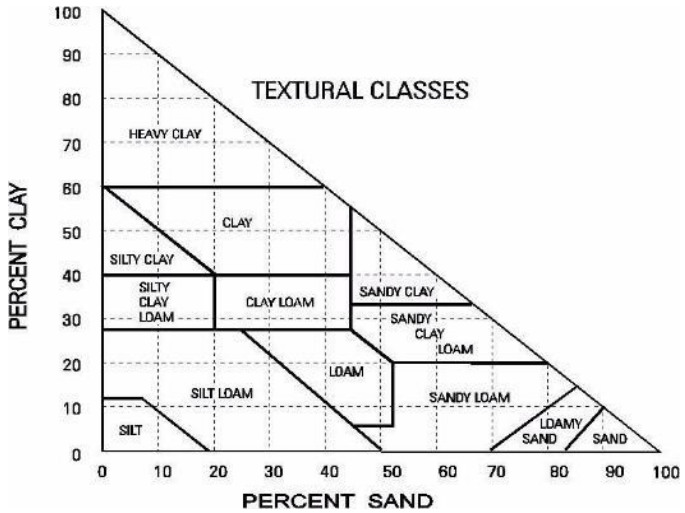

Figure 3.7 Soil textural classes used in the SIFT databased to classify soil types based on the percent of sand and clay in samples. Sourced from http://sis.agr.gc.ca/cansis/glossary/t/.

Table 3.3 Soil Drainage classifications (BC 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.

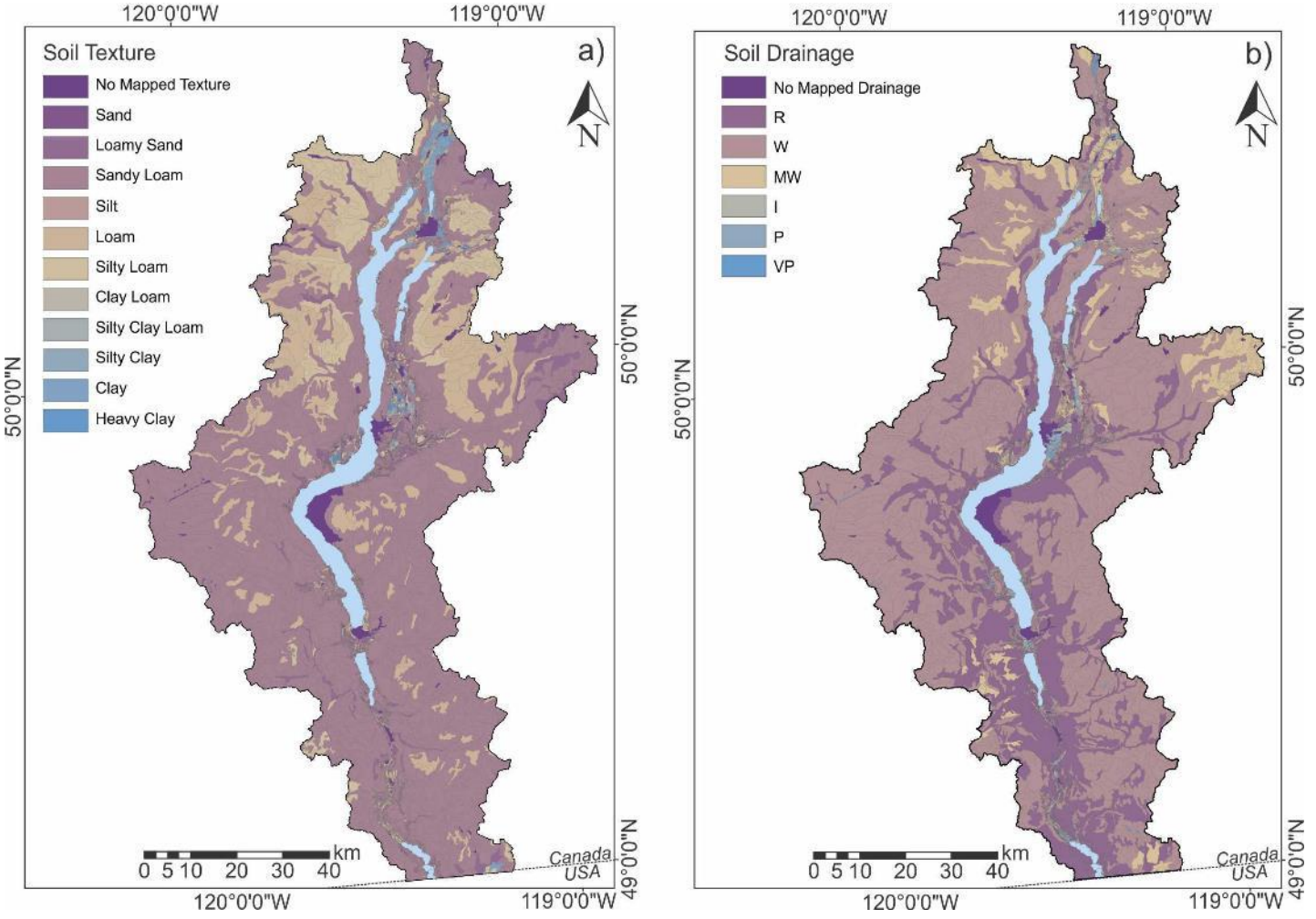

Figure 3.8 Soil texture polygons in the Okanagan from the SIFT database; legend items correspond to classification in the soil texture triangle (Figure 3.7) b) Soil drainage polygons in the Okanagan from the SIFT database; legend items correspond to Table 3.3.

Presence of Confining Unit

Flowing well occurrence was examined with respect to the presence of confining units of mapped aquifers (Figure 3.9a). The geologically controlled model for flowing artesian conditions is classically portrayed as a sloping confined aquifer. In this model 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). In lieu of using well logs at this regional scale an approach utilizing the extent of the aquifer polygons was used to determine the presence of a confining unit. Well logs were examined in select case study area to support the MCA results (see Chapter 5).

Aquifer polygons were obtained from DataBC as the 'Ground Water Aquifers' spatial coverage (BC 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. In this study, the descriptors were used to designate aquifers as either unconfined, confined or bedrock (Figure 3.9a). The presence of a confining unit comprising unconsolidated sediments 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.

A complicating issue for this analysis is that wells are not consistently assigned to specific aquifers in the BC Wells Database. Additionally, the aquifers do not have well defined depths spatially - only approximate depths across the entire aquifer are reported. Due to the complexity of the subsurface sediment and the large number of wells in each area, an approximation method had to be employed to determine if wells are completed in confined aquifers. Two methods were used:

1. The ‘Select’ tool in ArcMap was used to select the wells in confined aquifers. Then the same process was used to select the wells in unconfined aquifers. However, because there is overlap between the unconfined and confined aquifer polygons in both the Okanagan and the Fraser Valley, this resulted in a large number of wells being counted as both confined and unconfined. To address this, a second method was used.

2. The second method examined whether flowing wells are more likely to occur within a confined aquifer polygon than non-flowing wells. Any wells that occurred in a confined polygon were considered confined and any wells which occurred 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.

Stream Proximity

Flowing well occurrence was examined with respect to stream proximity (Figure 3.9b). 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 upwards, 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 1.2). By association, flowing artesian conditions may be more likely 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. The assumption is made in this study that all streams are gaining, and stream proximity was considered as a factor.

Stream locations were obtained through DataBC as the ‘Freshwater Atlas Stream Network’ spatial coverage (BC 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.

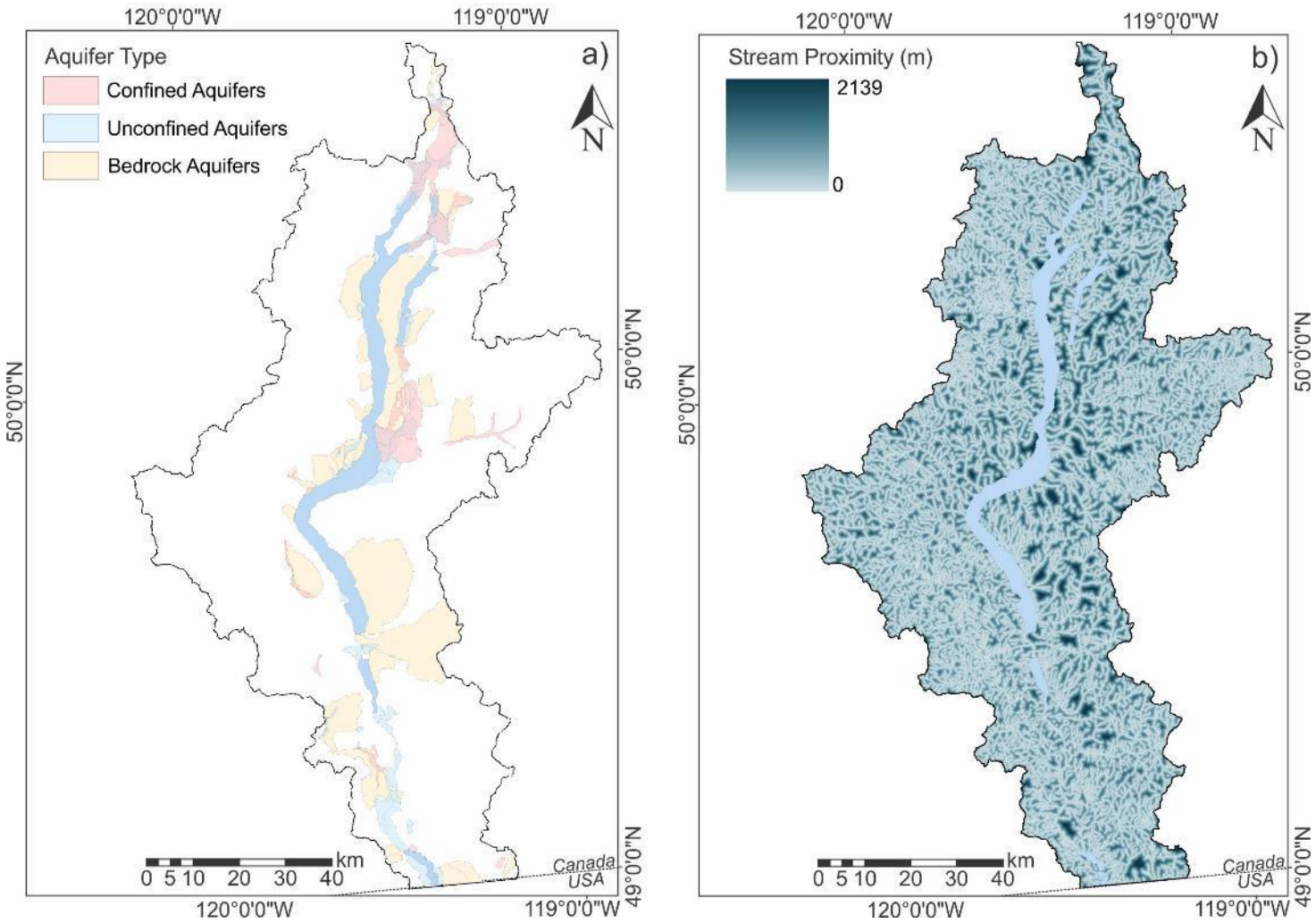

Figure 3.9 a) Aquifer types in the Okanagan b) Stream proximity in the Okanagan.

3.2.2. 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.

Alternative Hypothesis: The two data sets are from different populations.

Example Alternative Hypothesis: The elevations at flowing and non-flowing wells are from the different populations.

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 3.10. 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 3.10 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 B.

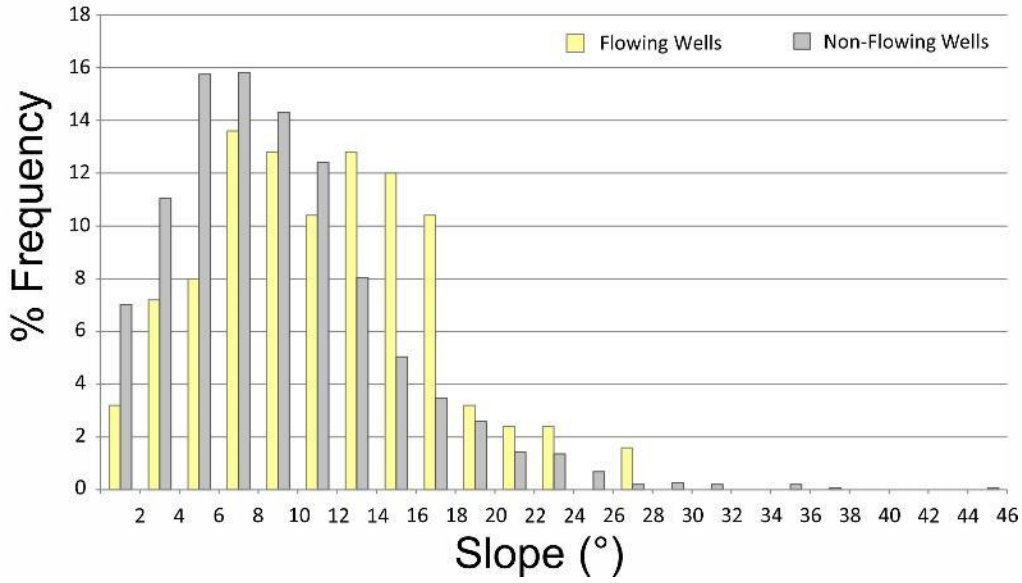

Figure 3.10 Percent frequency of the occurrence of flowing and non-flowing wells for the slope factor in the Okanagan Bedrock context.

3.2.3. Final Factors Used for Each MCA

A summary of the final factors used (>15% Wilcoxon significance level) for MCA in each hydrological context is provided in Table 3.4. Elevation and slope are used in the MCA at the original DEM cell size, but curvature was found to have more reasonable values (curvature ranging from approximately -8 to +8) at the larger cell size. The lineaments factor was analyzed as sets rather than the combined dataset due to

differences in spatial distributions and the different ranges in kernel densities between the lineament sets. This resulted in differences in the Wilcoxon Tests for each lineament set (see Section 3.3). In the final MCAs, soil drainage was used in preference to soil texture not only because drainage showed a stronger significance but because soil texture affects the drainage capacity of soil, and so texture is redundant. Neither of methods used to determine the presence of a confining layer guaranteed wells were categorically assigned to the correct aquifer, but the second method was preferred because it kept the size of the dataset consistent.

Table 3.4 Factors examined for the Multi-Criteria Analysis 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 (2x resolutions)	Y	Y	Y
Slope (2x resolutions)	Y	Y	Y
Curvature (2x resolutions)	Y	N	N
Flow Accumulation	Y	Y	N
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

* 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.

3.3. Determination of Relative Importance Factors and Their Weights

Once the statistically significant factors were identified (Table 3.4), 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 most 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 according to its relative importance to other factors. Column 1 in Table 3.5 (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 3.5 The Fundamental scale 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

In this study, Wilcoxon Test was used to test pairs of factors to determine the relative importance[2] of each factor. This is a novel approach that was taken to add a quantitative aspect to 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.

First, 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

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

Table 3.6 (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 3.6 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 3.2.2., but at varying significance levels. Tables 3.7 and 3.8 show the Wilcoxon Test results for the Okanagan Unconsolidated and Fraser Valley Unconsolidated, respectively.

Table 3.6 Okangan Bedrock signficance levels as determined by the Wilcoxon Test for the final factors used to determine the weights for the MCA. Green cells indicate the highest the 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 3.7 Okangan Unconsolidated signficance 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	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 3.8 Fraser Valley signficance 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 3.9, as the example. The pairwise comparison matrices for the Okanagan Unconsolidated and Fraser Valley Unconsolidated can be found in Appendix C. The upper matrix in Table 3.9 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 3.9 were determined quantitatively by comparing the highest achieved Wilcoxon significance levels from Table 3.6. 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 3.6) and were assigned a value of 1 in Table 3.9. 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 3.6), then a value of 3 (or 1/3) was assigned to the cell in Table 3.9. 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 3.6), and have a relative importance value of 3 (and 1/3) assigned in Table 3.9.

Table 3.9 Okanagan Bedrock pairwise comparison matrix for the 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 3.3). The yellow cell indicates the example calculation from Equations 3.6 – 3.7. The purple cells indicate the row sum calculated using Equation 3.8). The green cells indicate the final weights calculated from Equation 3.10.

	Elevation	Slope	Curvature	Flow Accumulation	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

The final step was to calculate the weights for each factor from the pairwise comparison matrix (lower part of Table 3.9). The weight for each factor was calculated using Equations 3.3 – 3.11. 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 3.3 and is shown as the blue cells in Table 3.9.

$$\sum_{i=1}^{n} R.I._i = R.I._1 + R.I._2 + \cdots + R.I._n \quad (3.3)$$

where:

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

$$\sum_{i=1}^{n} R.I._{Slope} = \frac{1}{7} + 1 + \frac{1}{9} + 1 + \frac{1}{3} + \frac{1}{5} + \frac{1}{3} = 3.12 \quad (3.4)$$

The relative importance value for each factor was then divided by the column sum, populating the lower portion of Table 3.9 to produce a normalised relative importance value (Equation 3.5). The normalised relative importance is shown as white cells in lower portion of Table 3.9.

$$N.R.I. = R.I_n \,/\, \sum R.I. \quad (3.5)$$

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 3.9.

$$N.R.I.(slope\ x\ slope) = R.I._{slope\ x\ slope} \,/\, \sum R.I._{slope} \quad (3.6)$$

$$N.R.I.(slope\ x\ slope) = \frac{1}{3.12} = 0.32 \quad (3.7)$$

Then the Row Sum of the lower table is calculated for each factor and is shown as purple cells in Table 3.9 (Equation 3.8).

$$\sum N.R.I._f = N.R.I._{f1} + N.R.I._{f2} + \cdots + N.R.I._{fn} \quad (3.8)$$

$$\sum N.R.I._{slope} = 0.24 + 0.32 + 0.22 + 0.32 + 0.35 + 0.29 + 0.35 = 2.08 \quad (3.9)$$

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 3.9 (Equation 3.10).

$$Final\ Weight = \sum N.R.I._f \,/\, \sum\left(\sum N.R.I._f\right) \quad (3.10)$$

$$Slope\ Weight = \frac{2.08}{(0.30+2.08+0.15+2.08+0.96+0.49+0.96)} = 0.30 \quad (3.11)$$

Table 3.10 shows the final weights for each factor. The ranges of Wilcoxon significance levels vary for each. The Okanagan Bedrock (Table 3.6) 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 3.10). The Okanagan and Fraser Valley Unconsolidated have more factors of equal importance. For example, in the Fraser Valley Unconsolidated context (Table 3.8), 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 3.7) has only two factors that did not contribute equally to the occurrence of flowing wells (flow accumulation and stream proximity).

Table 3.10 Weights determined for factor through the modified Analytical Hierarchy Process for the a) Okanagan Bedrock b) Okanagan Unconsolidated and c) Fraser Valley.

a)

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

b)

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

c)

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

3.4. 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. Bin intervals for the original scales of each dataset were determined through a sensitivity analysis conducted on the Fraser Valley Unconsolidated because of the larger dataset (Appendix D).

The bin intervals and standardized scores, as described below, 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 (Section 4.3). The remaining 75% of the data were used for the analysis (analysis wells). Table 3.11 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.

Table 3.11 The distribution of flowing wells that were reserved for analysis and for validitating 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

The percent frequency of flowing wells occurring in the bin intervals for each factor was first calculated (Equation 3.12). 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 3.13 – 3.14). 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 3.13. 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 3.14) 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.

$$\%\ Frequency = \frac{\#\ wells\ in\ BIN}{Total\ Wells} \tag{3.12}$$

$$Standardization\ Constant = \frac{Maximum\ Standardization\ Score}{Highest\ \%\ Frequency\ Value} \tag{3.13}$$

$$Standardized\ Score = \%\ Frequency\ * Standardization\ Constant \tag{3.14}$$

An example of the standardized scores for elevation in the Okanagan Bedrock is provided in Table 3.12. Sample calculations are shown in Equation 3.15 – 3.17. Table 3.12 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.

$$\%\ Frequency\ of\ elevations > 200 - 400\ masl = \frac{5}{94} = 5.3\ \% \tag{3.15}$$

$$Standardization\ Constant = \frac{100}{35.1\%} = 2.84 \tag{3.16}$$

$$Standardized\ Score\ = 5.3 * 2.84 = 15.2 \tag{3.17}$$

Table 3.12 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 3.13 – Table 3.15. Each factor's scale was converted to the standardized scale using the 'Reclassify' tool in ArcMap. These scores, coupled with the weights determined in Section 3.3, were used in the weighted linear equation (Section 3.5) to create the final MCA maps.

Table 3.13 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 3.14 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 3.15 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.

3.5. Weighted Linear Equations

Equation 3.18 (also shown in Figure 3.1) was used to develop three weighted linear equations (Equations 3.10 –3.12), one for each hydrogeological context. The equations were applied to every cell in the raster.

$$MCA\ Standardized\ Likelihood\ Score = [f_1 * (w_1)] + [f_2 * (w_2)] + \cdots [f_n * (w_n)] \quad (3.18)$$

where:

f_n is the standardised score of a factor

w_n is the weight determined for f_n.

Okanagan Bedrock

$$MCA\ Standardized\ Likelihood\ Score = [DEM * (0.04)] + [Slope * (0.30)] + [Curvature * (0.02)] + [Flow\ Accumulation * (0.30)] + [Lineament\ Density\ Set\ 1 * (0.14)] + [Lineament\ Density\ Set\ 2 * (0.07)] + [Lineament\ Density\ Set\ 3 * (0.14)] \quad (3.19)$$

Okanagan Unconsolidated

$$MCA\ Standardized\ Likelihood\ Score = [DEM * (0.18)] + [\ Slope * (0.18)] + [Flow\ Accumulation * (0.07)] + [TWI * (0.18)] + [Stream\ Proximity * (0.14)] + [Soil\ Drainage * (0.18)] + [Confining\ Unit * (0.18)] \quad (3.20)$$

Fraser Valley Unconsolidated

$$MCA\ Standardized\ Likelihood\ Score = [DEM * (0.16)] + [\ Slope * (0.16)] + [Flow\ Accumulation * (0.02)] + [TWI * (0.16)] + [Stream\ Proximity * (0.16)] + [Soil\ Drainage * (0.16)] + [Confining\ Unit * (0.16)] \quad (3.21)$$

Chapter 4. Multi-Criteria Analysis Maps

4.1. Map Classification and Percent Frequency Distributions

The standardized Multi-Criteria Analysis (MCA) scores are 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 3.19 – 3.21). 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 lower occurrences of flowing wells.

Figure 4.1 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 to occur than non-flowing wells. Areas on the maps with red cells were determined as being '*more likely than not'* 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 4.1).

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 likelihoods/MCA scores) and non-flowing wells with distributions skewed left (lower likelihoods). The distribution of the validation wells (Figure 4.2) is similar to that of the flowing wells (Figure 4.1) confirming the results of Figure 4.1. In both of these contexts, flowing wells have greater percent frequencies than non-flowing wells at standardized MCA scores > 70 (Figure 4.1). Therefore, scores > 70 (illustrated by the red arrows and dashed lines on Figure 4.1) are determined to be areas where flowing wells are more likely to occur. This marks the upper threshold for 'more likely than not' for the Okanagan and Fraser Valley Unconsolidated contexts.

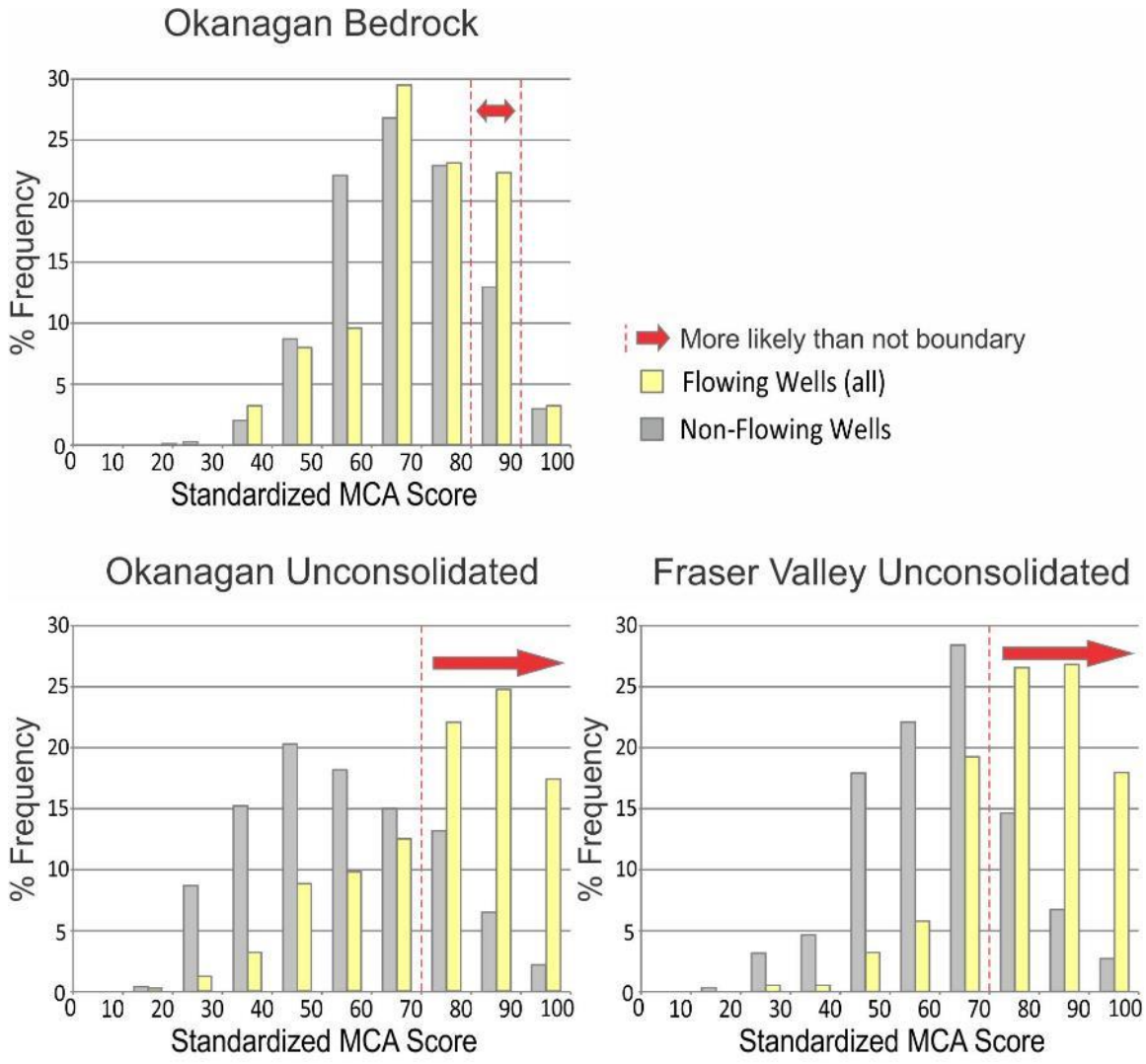

Figure 4.1 Percent frequency distributions of all flowing wells (validation and analysis combined) and non-flowing wells for each hydrogeologic context.

A second classification method was used for the Okanagan Bedrock context. This classification method also uses red cells to indicate where flowing wells are 'more likely than not' to occur, but uses a spectrum of red colours for different binned intervals rather than a single colour. The Okanagan Bedrock context also displays two distinctly skewed distributions but they are less visually pronounced. In this context flowing wells have greater percent frequencies at standardized MCA scores > 60. However, unlike the unconsolidated contexts, two of the binned intervals (70 - 80 and 90 - 100) have percent frequencies that approximate each other, in addition to the 90 – 100 binned interval having low well occurrence (<5%). Additionally, the validation wells for standardized

MCA scores between 60 – 70 occur at percent frequencies less than non-flowing wells (Figure 4.2), indicating conflicting results for where flowing wells are ‘more likely than not’ to occur. For these reasons, 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. Bin intervals 60 – 70 and 70 – 80 were both included in the ‘more likely than not’ classification despite the similar occurrences between flowing and non-flowing wells due to the high occurrence of flowing wells in these intervals. Excluding scores > 90 really does not impact the final map due to the low occurrence of wells in this range.

One explanation for the Okanagan Bedrock context not having the same distribution as the two unconsolidated contexts is because the flowing bedrock wells occur in small clusters that are dispersed across a wider range of the factors. This results in the factor standardization (Section 3.4) having a higher range of standardized intervals with moderate standardized factor scores. For example, the Fraser Valley Unconsolidated has only two binned intervals with standardized scores > 50 (Table 3.15) and the Okanagan Unconsolidated contexts only has one binned interval with a standardized score > 50 (Table 3.14). However, the Okanagan Bedrock has three binned intervals > 50 (Table 3.13) and this trend continues across the majority of factors (see Appendix B for histograms of individual factors). This results in the Okanagan Bedrock context not having a distribution of flowing wells that is as clearly skewed to the right (i.e. with higher standardized MCA scores).

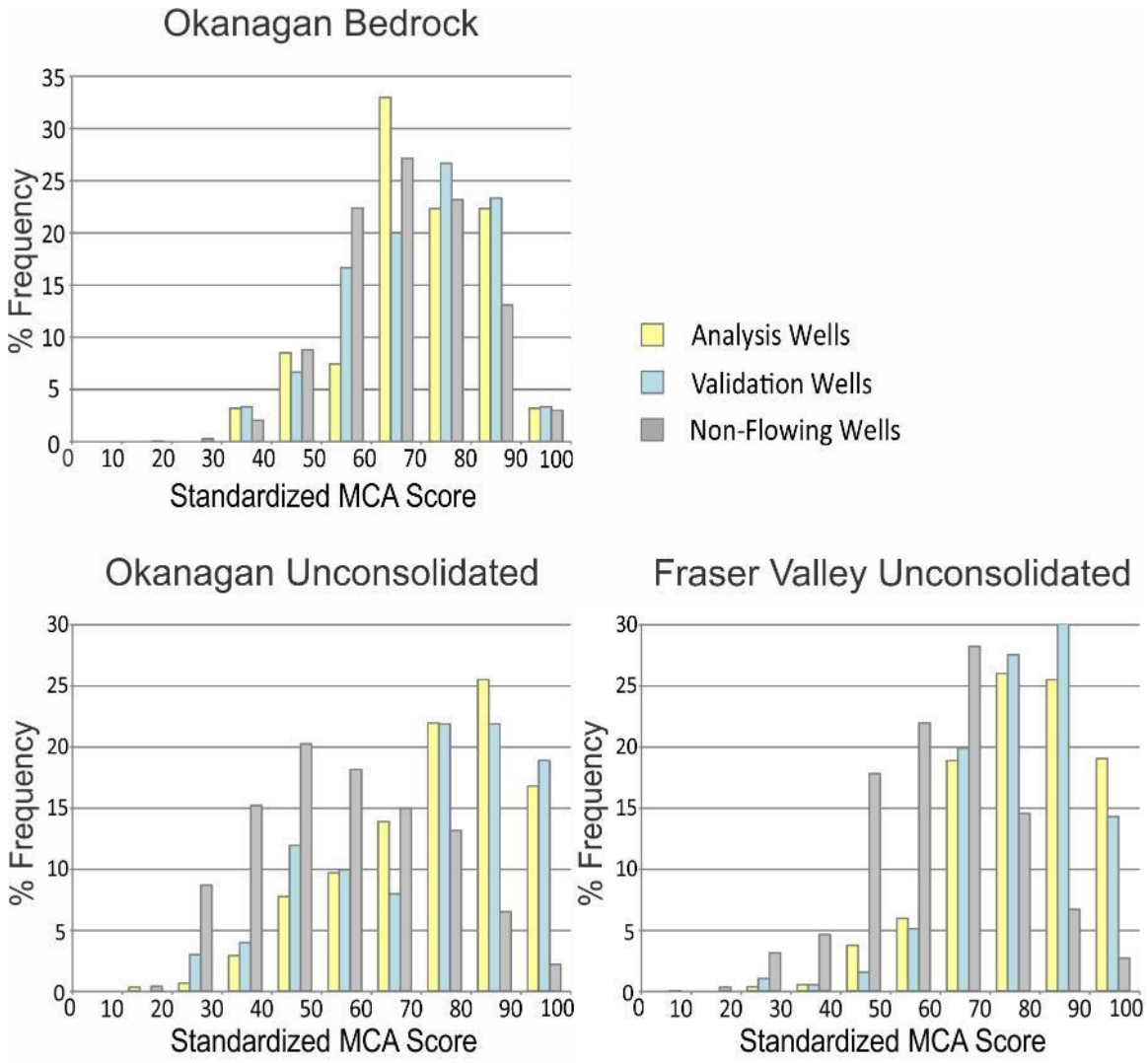

Figure 4.2 Percent frequency distributions of the analysis wells, validation wells, and non-flowing wells for each hydrogeologic context. The validation wells have a similar distribution to the analysis wells.

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 4.1). 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.

The skews in the distributions and the predominately higher percent frequency occurrences of flowing wells at higher standardized MCA scores indicate that the MCA maps met the objectives they were designed for. The two distinct distributions preliminarily showcase the results of the Wilcoxon Test outlined in Section 4.4 and indicate that higher standardized MCA scores do relate to a higher likelihood of encountering flowing artesian conditions. However, statistical validation is required in order to draw more conclusive results.

4.2. Standardized MCA Score Statistics

The score statistics for flowing wells were compared with the score statistics for the entire map (standardized MCA scores calculated using Equation 3.19 – 3.21). The standardized MCA score statistics for each hydrogeological context are presented in Table 4.1. A wide range of standardized MCA scores is possible across each hydrogeologic context, indicating that the maps are able to capture high and low likelihood areas. Each hydrogeologic context has mean flowing well scores that are higher than the mean map scores indicating a preliminary conclusion that the methods are able to identify higher likelihood of flowing artesian areas. 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 having higher likelihoods.

Table 4.1 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

4.3. Map Validation

4.3.1. Method

The final step identified for the MCA workflow (Figure 3.1) is to validate the maps produced. The map validation 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 hypotheses posed for the first objective are:

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

Alternative Hypothesis: The analysis wells and the validation wells are from the different populations.

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 hypotheses posed for the first test of the second objective are:

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

Alternative Hypothesis: The validation wells and the non-flowing wells are from the different populations.

The hypotheses posed for the second test of the second objective are:

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

Alternative Hypothesis: The flowing wells and the non-flowing wells are from the different populations.

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

4.3.2. Wilcoxon Results

The Wilcoxon Test results are displayed in Table 4.2. Each hydrogeologic context met the desired outcome at an acceptable significance level. The Okanagan Bedrock context achieved the lowest significance level (15%), while the Okanagan Unconsolidated and Fraser Valley Unconsolidated contexts both achieved a 5% (the highest) significance level. The Okanagan Bedrock was limited by the Wilcoxon Test comparing the validation and non-flowing wells as the other two tests passed at a significance level of 5%, This is likely because of the small sized validation well data set. The Wilcoxon Test results indicate that each MCA map met the goals they were meant to achieve with varying, but high success.

Table 4.2 Wilcoxon Test results for each hydrogeologic context for each objective and test with the highest achieved signficance level indicated.

	Highest Achieved 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	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

4.4. Discussion of Map Results

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 to occur and blue cells indicate areas where

non-flowing wells are more likely to occur. Chapter 5 takes a closer look at the map results for specific regions in each hydrogeologic context.

4.4.1. Okanagan Bedrock Context

The MCA map for the Okanagan Bedrock context (Figures 4.3 and 4.4) 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 3.19). Therefore, any cells falling outside the extent of lineament density map will only be able to achieve a maximum MCA score of 75. As a result, the extent of the lineament datasets approximates the periphery of the red banding in the Okanagan Bedrock MCA map.

A moderate amount of the area outside the mapped lineament extent has scores > 45. So, given that a standardized MCA score between 80 – 90 is required to be mapped as high likelihood, this would require all lineament sets to achieve a maximum standardized score of 35 in order to be classified as high likelihood. Therefore, if the lineament dataset was expanded to include the periphery areas, then there could be additional areas of high likelihood.

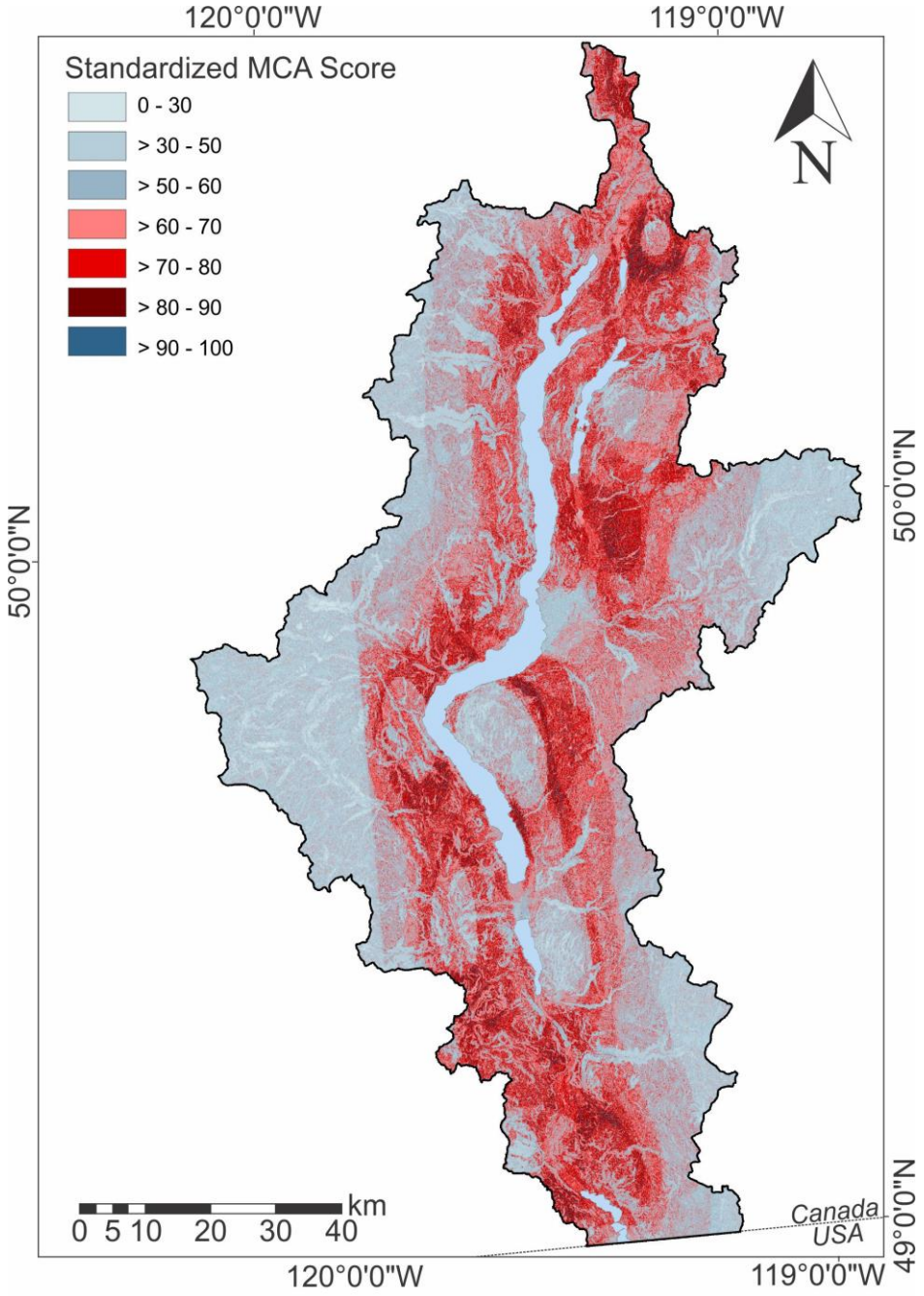

Figure 4.3 Okanagan Bedrock MCA map. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

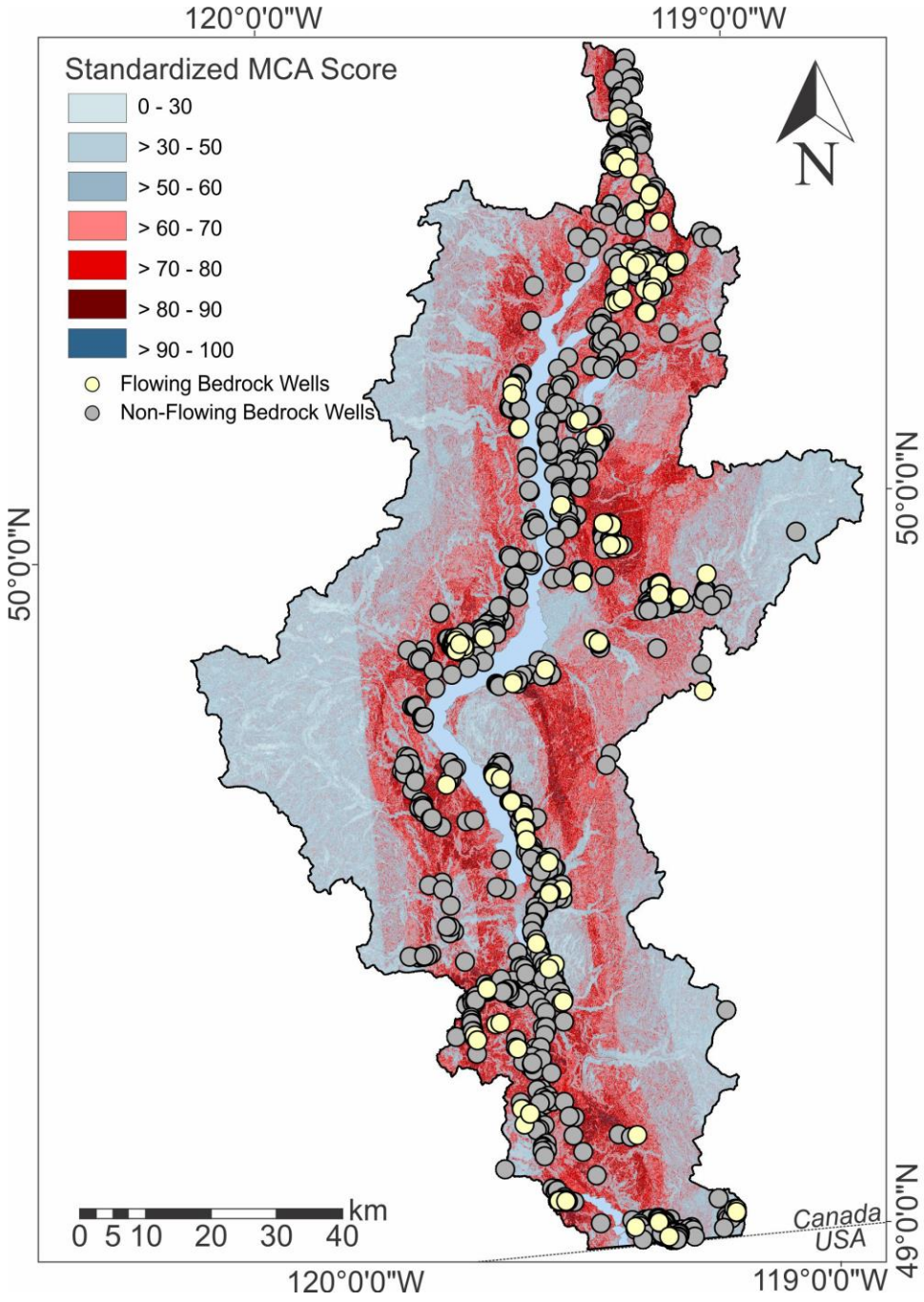

Figure 4.4 Okanagan Bedrock MCA map showing the locations of flowing bedrock wells. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

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 high likelihood (Figure 4.4); however, the mapped high likelihood areas do not appear as clusters around the flowing bedrock wells. Rather these high likelihood 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 3.19). Flow accumulation varies significantly between adjacent cells, and so the raster map appears grainy at small scales (sees Figure 3.4a). Curvature also results in significant differences between adjacent cells (see Figure 3.3c); however, curvature was assigned a relatively low weight (0.02 in Equation 3.19) and so does not impact the final map noticeably.

2. Standardized scores are more moderate (Section 3.5; Section 4.1) 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. the unconsolidated contexts). This results in the more dispersed appearance of the mapped 'higher likelihood' areas.

In addition to flowing wells having similar spatial distributions to non-flowing wells, they also have somewhat different depth distributions. The depth statistics for the Okanagan Bedrock context are displayed in Table 4.3. 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 4.5). 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 high likelihood regardless of well depth, and that flowing artesian conditions are possible in all bedrock aquifers through much of the Okanagan.

Table 4.3 Okanagan Bedrock depth statistics for flowing and non-flowing wells. Units for depths are metres below ground surface (mbgs).

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

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

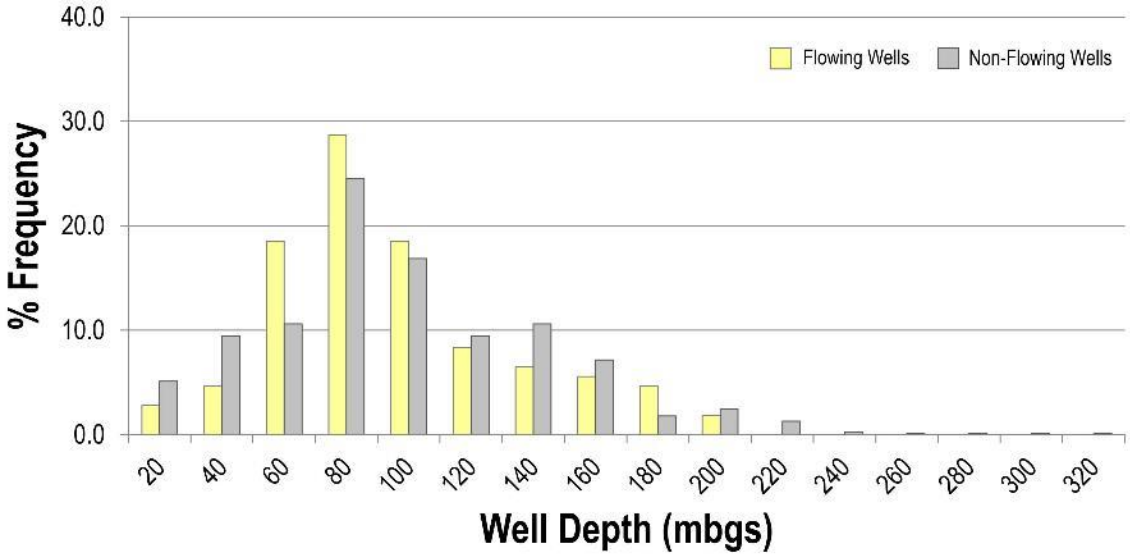

Figure 4.5 Percent frequency distribution of flowing and non-flowing well depths in the Okanagan Bedrock context. Units in metres below ground surface.

4.4.2. Okanagan Unconsolidated Context

The MCA map for the Okanagan Unconsolidated context (Figures 4.6 and 4.7) shows several isolated areas of high likelihood, primarily within the valley bottom, but smaller areas of high likelihood also occur in the major (regional scale) gullies 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.

The majority of the flowing wells cluster within the higher likelihood areas (Figure 4.7). 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 mapped as high likelihood that could be considered for a well drilling advisory. Well drilling advisories for flowing artesian conditions are given further consideration in Chapter 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 4.7 to Figure 4.8. The majority of the confined aquifers have flowing wells within their polygon boundaries (Figure 4.8) 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.

The majority of the high likelihood areas 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.

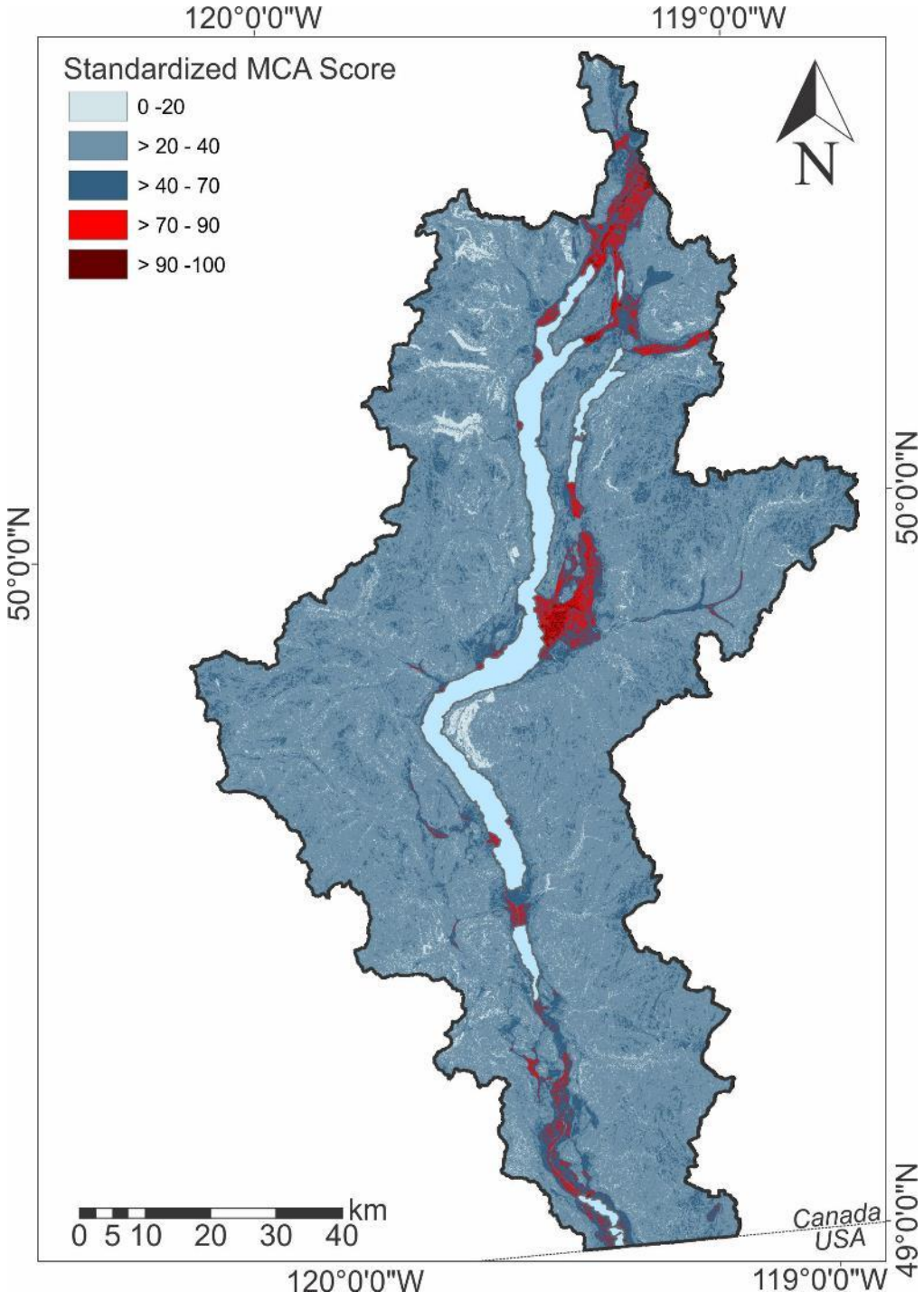

Figure 4.6 Okanagan Unconsolidated MCA map. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

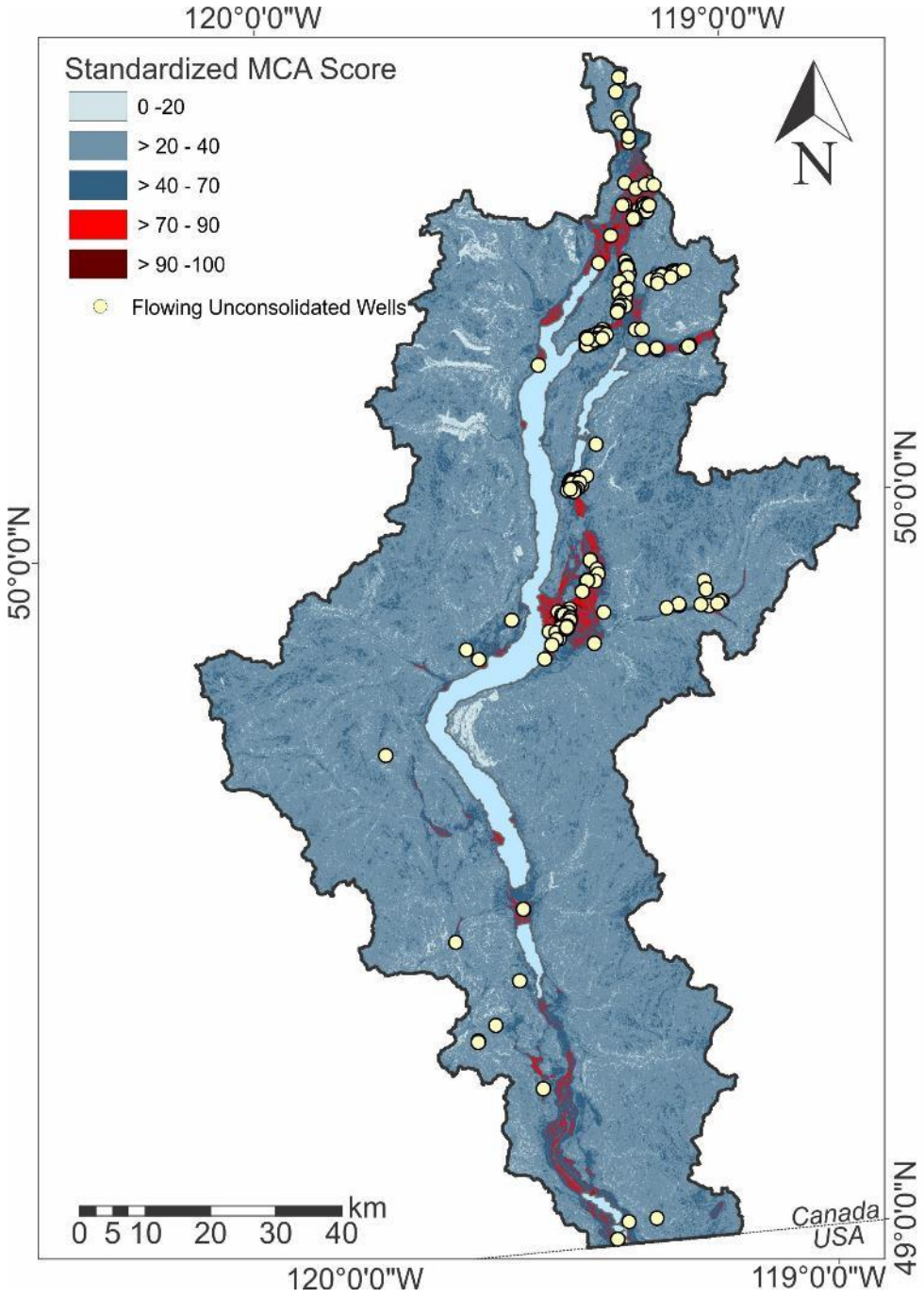

Figure 4.7 Okanagan Unconsolidated MCA maps showing the locations of flowing wells in unconsolidated materials. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

A few areas in the Okanagan Unconsolidated context are mapped as high likelihood, yet do not have any flowing wells. Notably the ‘higher likelihood’ strip stretching north from the Canada/USA border through Oliver (Figure 4.6 and 4.7). Interestingly, there is no mapped confining unit present. Therefore, the high standardized values for each of the other factors (see Table 3.14) 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 interval and contributed a low score to the entire location. The absence of flowing wells along this strip 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, or by regulated flow along Okanagan River.

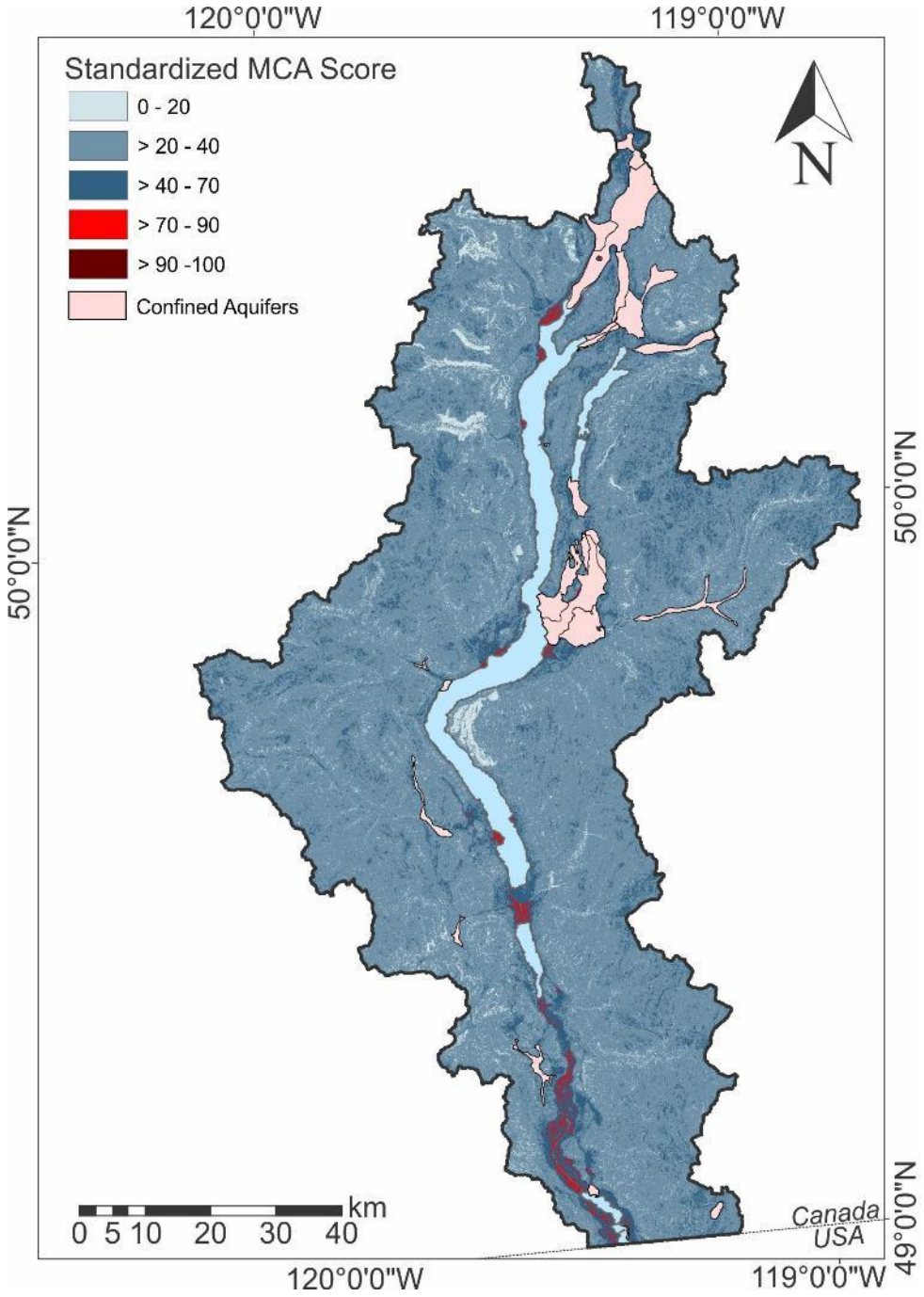

Figure 4.8 Okanagan Unconsolidated MCA results showing the mapped confined aquifers overlapping the high likelihood areas.

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 (i.e. a greater range) (Table 4.4). 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 4.9). 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 4.9).

Table 4.4 Depth statistics for flowing and non-flowing wells for the Okanagan Unconsolidated context. Units for depths are metres below ground surface (mbgs).

	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 (mbgs)	32	21
Standard Deviation (mbgs)	22	50

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

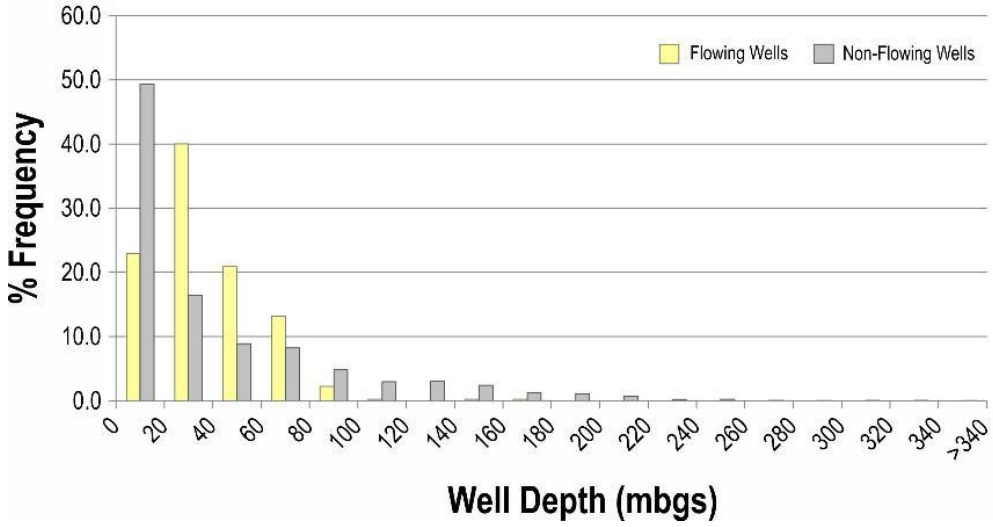

Figure 4.9 Percent frequency distribution of flowing and non-flowing well depths for the Okanagan Unconsolidated context. Units in metres below ground surface (mbgs).

4.4.3. Fraser Valley Unconsolidated Context

Flowing wells in the Fraser Valley Unconsolidated context occur mostly within the red areas associated with high likelihoods (Figures 4.10 and 4.11). 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 Valley and 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. This region is mapped as high likelihood because the factors share many common values with the high likelihood area in the west, i.e. they are both flat, have low elevation, are overlain by a confining unit, and have similar stream densities. Although, there are a few sporadic flowing wells in the Chilliwack-Sumas valley the mapping results may be inaccurately high here as the flowing well density is much lower.

The higher weight of the stream factor (relative to the other factors) in the Fraser Valley Unconsolidated context results in the map having higher likelihood areas (red cells) concentrated around streams. This results in the map having string-like zones of higher likelihood in locations where all other factors remain relatively constant.

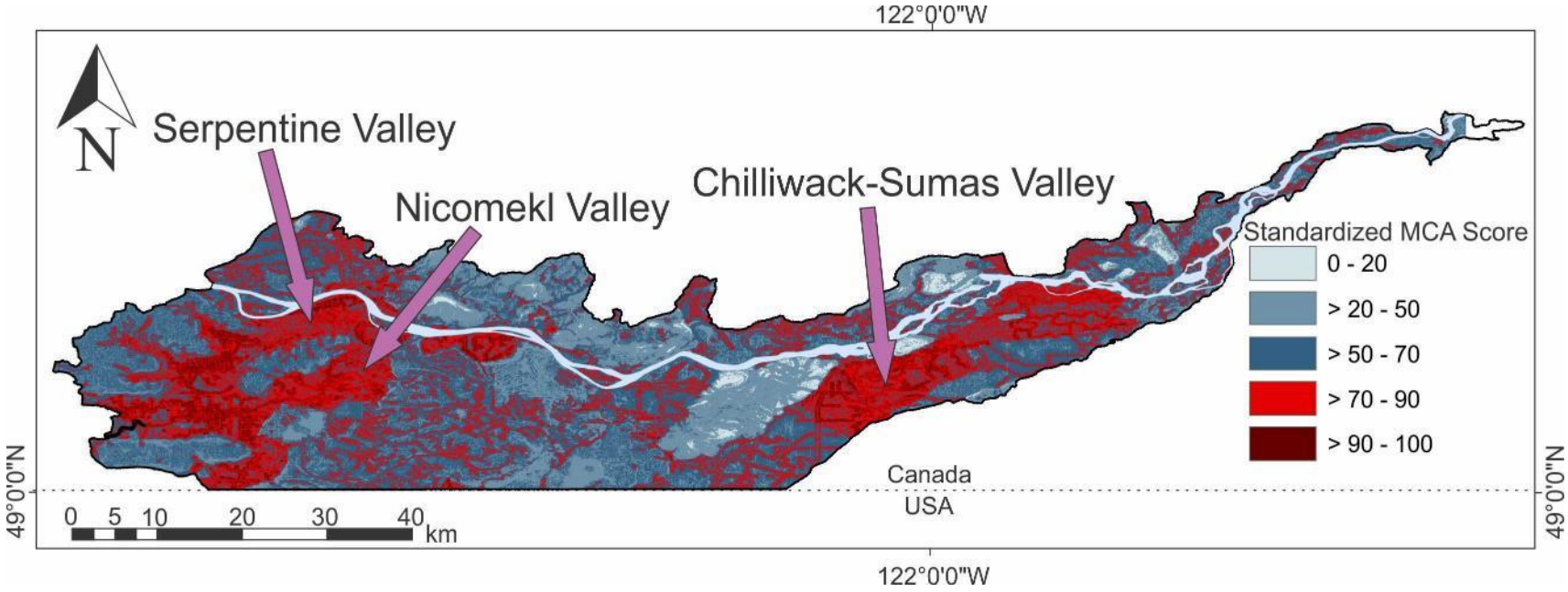

Figure 4.10 Fraser Valley Unconsolidated MCA map. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

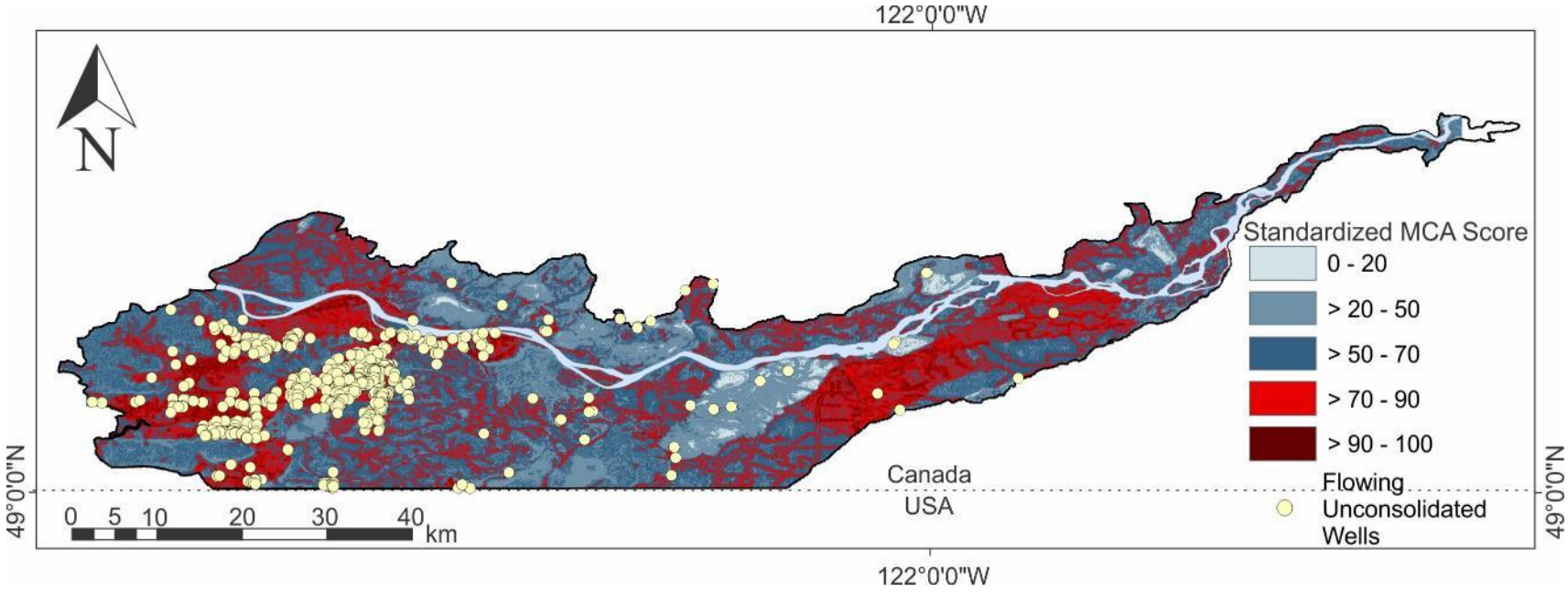

Figure 4.11 Fraser Valley Unconsolidated MCA map showing the locations of flowing wells in unconsolidated materials. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

Flowing wells in the Fraser Valley Unconsolidated context generally occur deeper than their non-flowing counterparts (Table 4.5). Flowing wells are consistently more likely to occur (higher percent frequencies) at depths greater than 60 mbgs. 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 higher likelihood. 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.

Table 4.5 Depth statistics for flowing and non-flowing wells in the Fraser Valley Unconsolidated context. Units for depths are metres below ground surface (mbgs).

	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 (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

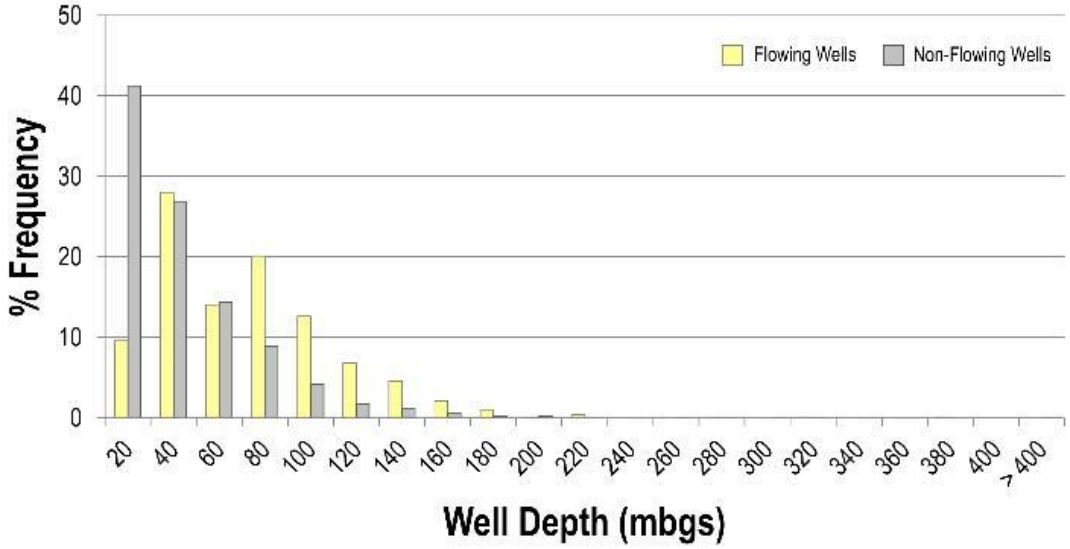

Figure 4.12 Percent frequency distribution of flowing and non-flowing well depths for the Fraser Valley Unconsolidated context. Units in metres below ground surface (mbgs).

4.5. Influential Factors

Chapter 3 presented the weighting for each factor in each hydrogeologic context (Table 3.10). 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.

4.5.1. 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 between 6 – 18° and their occurrence drops off sharply at greater slope angles (Figure B.1), although the highest standardized raster score is for slopes between 10 – 14° (Table 3.13). Flowing wells occur mostly at the mid range flow accumulations values (1-100) and the highest standardized raster score is between 1-10 (Table 3.13). 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 B.3), which is also the range of the highest standardized raster scores (Table 3.13). Lineament set 3 has flowing wells occurring most frequently between densities of 20 – 30 m/m^2 (Figure B.3), which is also the range of the highest standardized raster scores (Table 3.13).

4.5.2. 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 3.14; Figure B.4). Flowing wells occur most frequently at low slopes ranging from 0 – 4° (Figure B.4; Table 3.14) and at moderate TWI values (6-8; Figure B.5; Table 3.14). Flowing wells occur most frequently in poorly and well drained soils, but only in poorly drained soils do flowing wells occur more frequently (3x) than non-flowing wells (Figure B.5; Table 3.14). Finally, flowing wells are more than twice as likely to occur if there is a confining unit present (Figure B.6).

4.5.3. 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 B.6; Table 3.15). Flowing wells occur most frequently at low slopes, but only occur more frequently than non-flowing wells at slopes < 2° (Figure B.6; Table 3.15). 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 B.7; Table 3.15). Flowing wells are more likely to occur within 200 m of a stream (Figure B.8; Table 3.15). Poorly drained soils have the highest occurrence of flowing wells, but imperfectly, poorly and very poorly drained soils have higher occurrences of flowing wells than non-flowing wells. Lastly, Flowing well are more likely to occur if there is a confining unit present (Figure B.8; Table 3.15).

Chapter 5. Case Studies and Flowing Well Advisories

This chapter provides site specific examinations of a few select areas that are mapped as 'more likely than not' to have flowing wells from Chapter 4. The sites are viewed in conjunction with well drilling advisories and provide insight and recommendations for advisories where none exist. The locations are classified as either geologically controlled, topography controlled or a combination of the two end members. The case studies are evaluated with either two-dimensional or three-dimensional (2D or 3D) conceptual models of the area. Models were made in either Leapfrog (Seequent, 2019) or GMS (Aquaveo, 2007). 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, Aquifer 33 and 58 are examined using a Leapfrog model. The locations of these case studies are presented in Figure 5.1.

5.1. Overview of Flowing Well Advisories

The BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development and the BC Ministry of Environment and Climate Change Strategy 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, four of which are within the study areas. The Okanagan has well drilling advisories for Vernon Creek, Coldstream, and Lower Mission Creek area of Kelowna. The Fraser Valley has a single flowing well advisory for Surrey and Langley. The locations of these advisories are identified on Figure 5.1. 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.

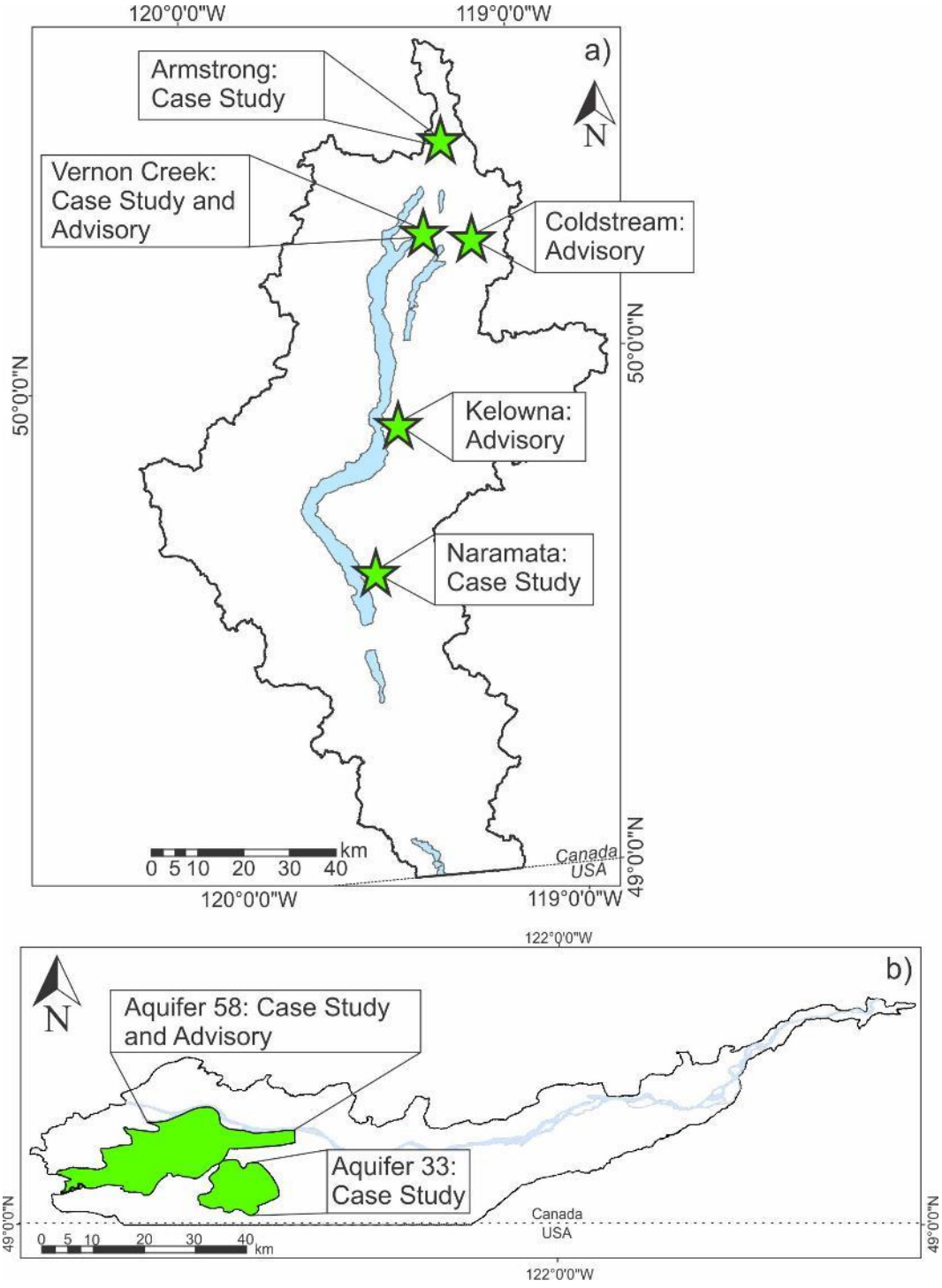

Figure 5.1 Map of case study areas and flowing well advisory locations in a) Okanagan Basin and b) the Fraser Valley.

5.2. Okanagan Bedrock

5.2.1. 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 contains 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 5.2: 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 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 Province concerning drainage issues in the Naramata region. This report details an account from a local resident regarding a flowing well in the area referred to as the 'Workman Well' (Tetra Tech, 2019). The report identifies a flowing well which had 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 'Workman Well'. Indeed, there are four flowing wells on the Workman property within the GWELLS database; two of these wells have the surname listed as Phil Workman Sr. the other two wells have the surname listed as a holdings company. These four wells consist of the flowing wells used to create the conceptual model presented in this section.

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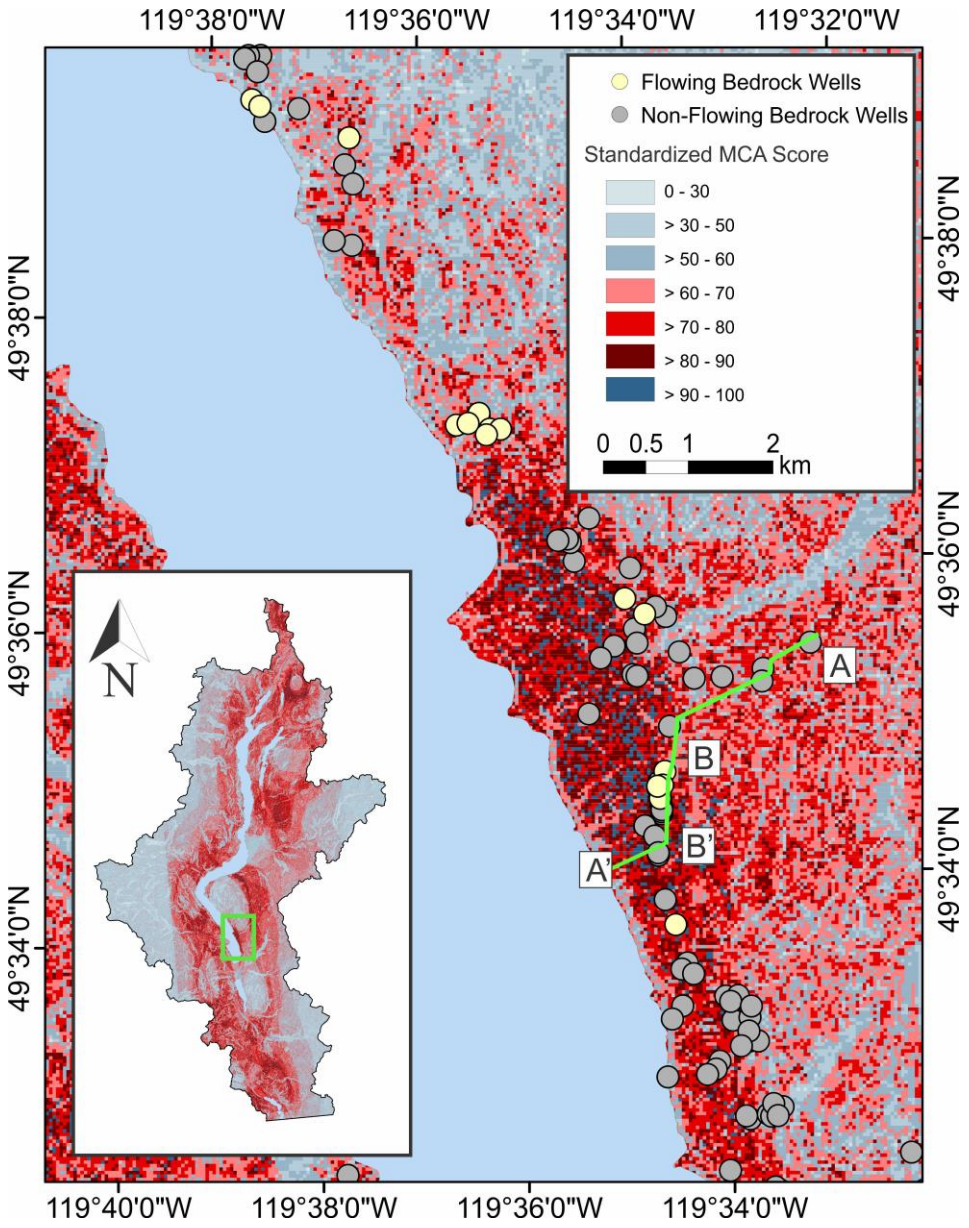

Figure 5.2 Okanagan Bedrock context MCA mapping results in the Naramata region showing flowing and non-flowing bedrock wells. The inset map shows the extent of Naramata (green rectangle). The green line represents the transect for the 2D conceptual model (Figure 5.3)

Naramata has a relatively large cluster of flowing bedrock wells (Figure 5.2), although there are more non-flowing well than flowing wells (84 vs 16; Table 5.1). Flowing and non-flowing wells in Naramata are co-located through the region. The statistics provided in Table 5.1 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 metres below ground surface (mbgs). Non-flowing wells have a median depth of 98 mbgs (Table 5.1); however, the flowing wells occur over a greater range of depths and have a smaller standard deviation.

Table 5.1 Depth statistics for flowing and non-flowing wells in Naramata (area shown in Figure 5.2). Units for depths are metres below ground surface (mbgs).

	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 (mbgs)	79	98
Standard Deviation (mbgs)	30	42

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 Figures 3.5 and 3.6) 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. Given these conditions it is likely that the area can be classified as a geologically controlled model for flowing artesian conditions.

A 2D conceptual model for flowing artesian conditions in fractured bedrock was developed in GMS (Figure 5.3). 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.

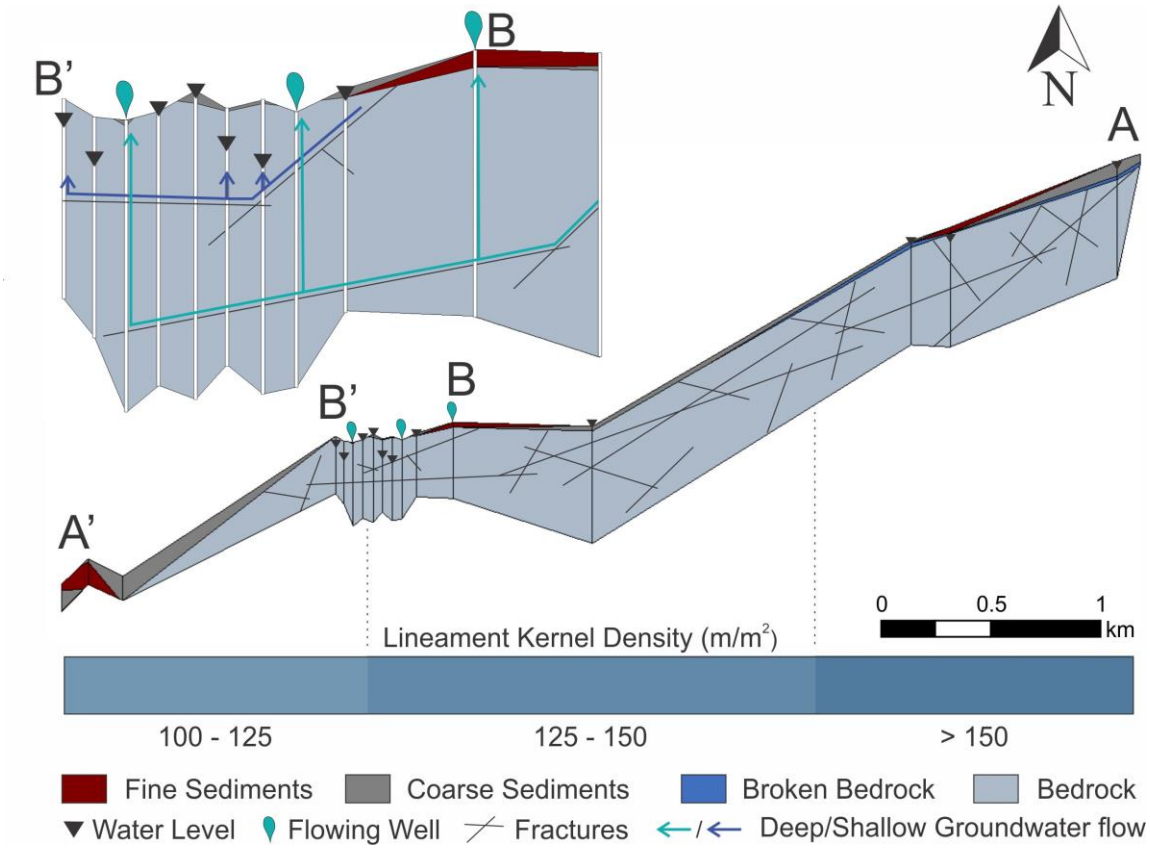

Figure 5.3 Two-dimensional (2D) conceptual model of flowing bedrock wells in Naramata. Lineament kernel density values determined in Figure 3.5b are shown along the bottom of the figure. The larger scale inset shows conceptual groundwater flow paths in the fractures which would lead to flowing and non-flowing wells. Model is constrained by ground surface elevation and the depth of the wells. (2x vertical exaggeration).

No Well Drilling Advisory currently exists for Naramata. While Naramata only has 16 flowing wells, these wells account for 13% of all flowing bedrock wells in the Okanagan Basin. 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 5.3 shows, flowing wells can occur immediately beside non-flowing wells of the same depth. Therefore, when drilling in fractured bedrock a driller is essentially playing a game of roulette on whether they will encounter flowing artesian conditions or not. A Well Drilling Advisory for Naramata would help to communicate this risk to drillers.

5.3. Okanagan Unconsolidated

5.3.1. 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[3] (Province of BC, 2018d). The advisory simply showcases the location and depths of the flowing wells in the vicinity of Vernon Creek but does indicate 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 BC, 2018d).

Figure 5.3 shows the MCA results for Vernon Creek. The MCA results for Vernon Creek are consistent with the findings from Chapter 4, which indicated that the MCA maps accurately portray the extent of flowing artesian conditions. The flowing wells tend to occur in the higher likelihood areas while non-flowing wells tend to cluster around the outer edges of the higher likelihood area. The extent of the high likelihood areas (red cells in Figure 5.3) does not account for discontinuities in the confining unit as noted above, and therefore provides a conservative representation of flowing artesian conditions.

[3] Despite the well drilling advisory including bedrock wells, there are no flowing bedrock wells in GWELLS in this area.

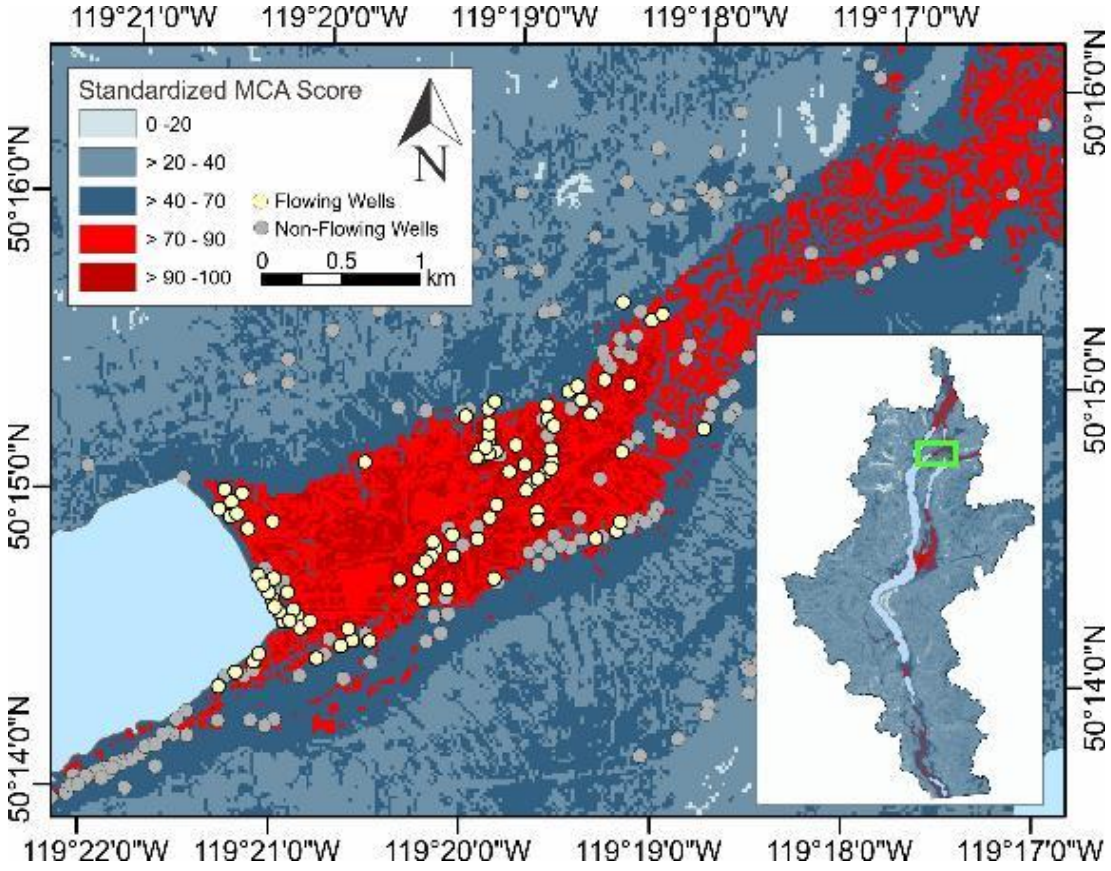

Figure 5.3 Okanagan Unconsolidated context MCA map results in Vernon Creek with flowing and non-flowing wells in unconsolidated materials. The inset map shows the extent of Vernon Creek (green rectangle). The extent of this figure approximates the extent shown in the Well Drilling Advisory for Vernon Creek (Province of BC, 2018d).

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 5.2). 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 5.2 Depth statistics for flowing and non-flowing wells in Vernon Creek (area shown in Figure 5.3) for the Okanagan Unconsolidated context. Units for depths are metres below ground surface (mbgs).

	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 (mbgs)	49	10
Standard Deviation (mbgs)	21	26

Because the flowing wells in Vernon Creek occur in a confined aquifer, the flowing artesian conditions can be classified as a geologically controlled; however, topography also appears to play a role. For example, the higher likelihood area mapped in the red cells outlines a valley bottom that slopes westward (Figure 5.3). 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. This indicates that aspects from both conceptual models (topographically controlled and geologically controlled) likely influence flowing artesian conditions in the Vernon Creek area.

5.3.2. 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. Flowing wells in the area occur in bedrock and unconsolidated materials, but the MCA map for the Okanagan Unconsolidated is used for comparison (Figure 5.4). However, both bedrock and unconsolidated wells were used for the

Leapfrog modelling. This case study is used to examine the importance a confining unit plays in determining the extent of flowing artesian conditions.

There are 11 flowing bedrock wells and 42 flowing wells in unconsolidated material (Table 5.3). The bedrock wells (not shown in Figure 5.4) 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 4 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) (Figure 5.4). This indicates that the system is likely representative of a geologically controlled model.

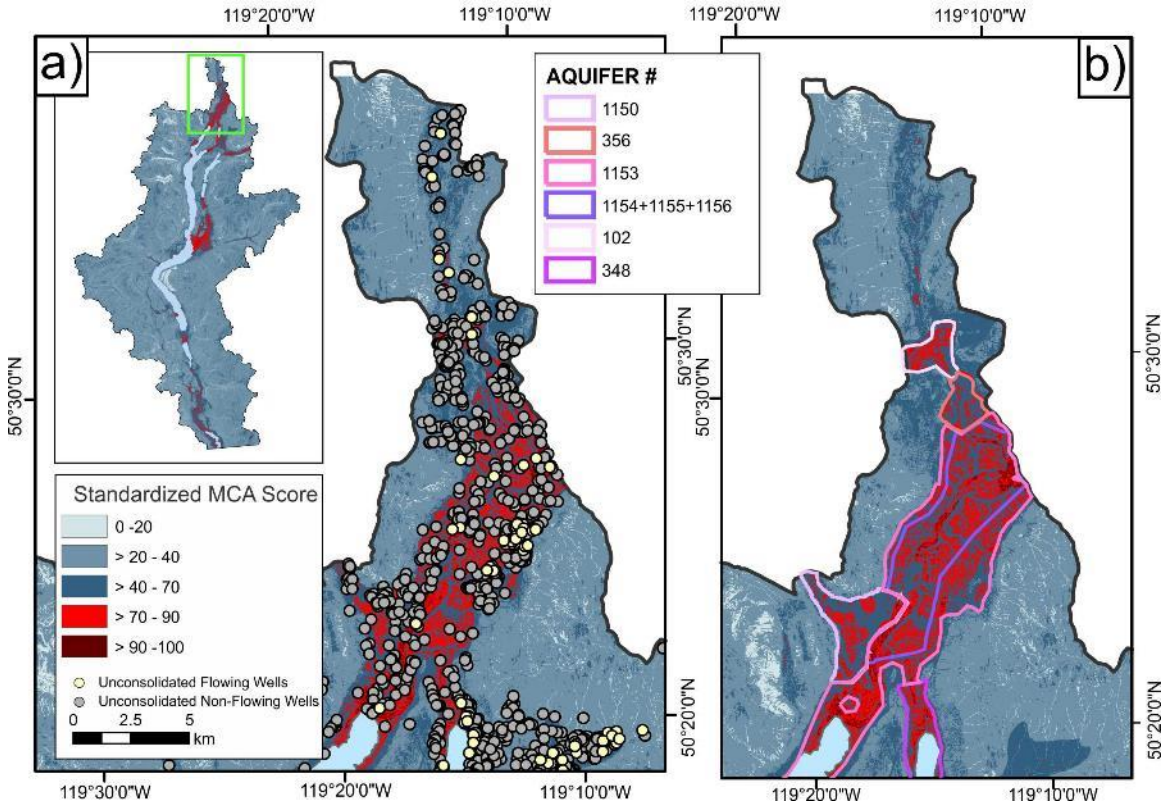

Figure 5.4 Armstrong MCA map for Okanagan Basin Unconsolidated context. Aquifer #'s are listed from North to South. One Aquifer polygon is presented for 1154, 1155, and 1156 due to their similar extent.

Unconsolidated flowing wells in the Armstrong area tend to be deeper, with greater median depths than their non-flowing counterparts (Table 5.3). Bedrock flowing wells have shallower median depths than their non-flowing counterparts but are deeper than the unconsolidated flowing wells.

Table 5.3 Depth statistics for flowing and non-flowing wells in Armstrong (area shown in Figure 5.4) 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 (mbgs)	52	47	79	85
Standard Deviation (mbgs)	28	52	52	53

5.3.3. Armstrong Leapfrog Model

A 3D 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 would likely not have significant training in sediment classification. Therefore, it is assumed that ‘glacial’ refers to till, as till is a common unit identified by drillers in BC. Till is an unsorted sediment,

which is usually compacted 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.

The extent of the modelled confining unit is presented in Figure 5.5a. Figure 5.5b shows the mapped confined aquifers (Aquifers 102, 348, 349. 356. 1150, 1153, 1154, 1155, 1156 from GWELLS) superimposed. The Leapfrog modelling indicates a more expansive extent of the confining unit than suggested by the extent of the confined aquifers; the modelled confining unit extends to the unconsolidated flowing wells north of the mapped confined aquifers. The confining unit is continuous in the locations where the confined aquifers are mapped but becomes less continuous farther north outside the boundary of the mapped aquifers. It should be noted that Leapfrog has difficultly handling boundaries beyond the DEM[4] as there are no well lithologies or topography beyond the DEM to constrain and inform the extent of the modelled lithologies. Thus, the extent of the confining unit beyond the boundaries of the DEM should not be assumed correct. Nonetheless, the modelling results suggest that there may be an additional confined aquifer (area identified with red arrows in Figure 5.5b) or that the extent of one of the known confined aquifers (most likely Aquifer 102) needs to be extended.

[4] The DEM was clipped to the Okanagan Basin outline for this study.

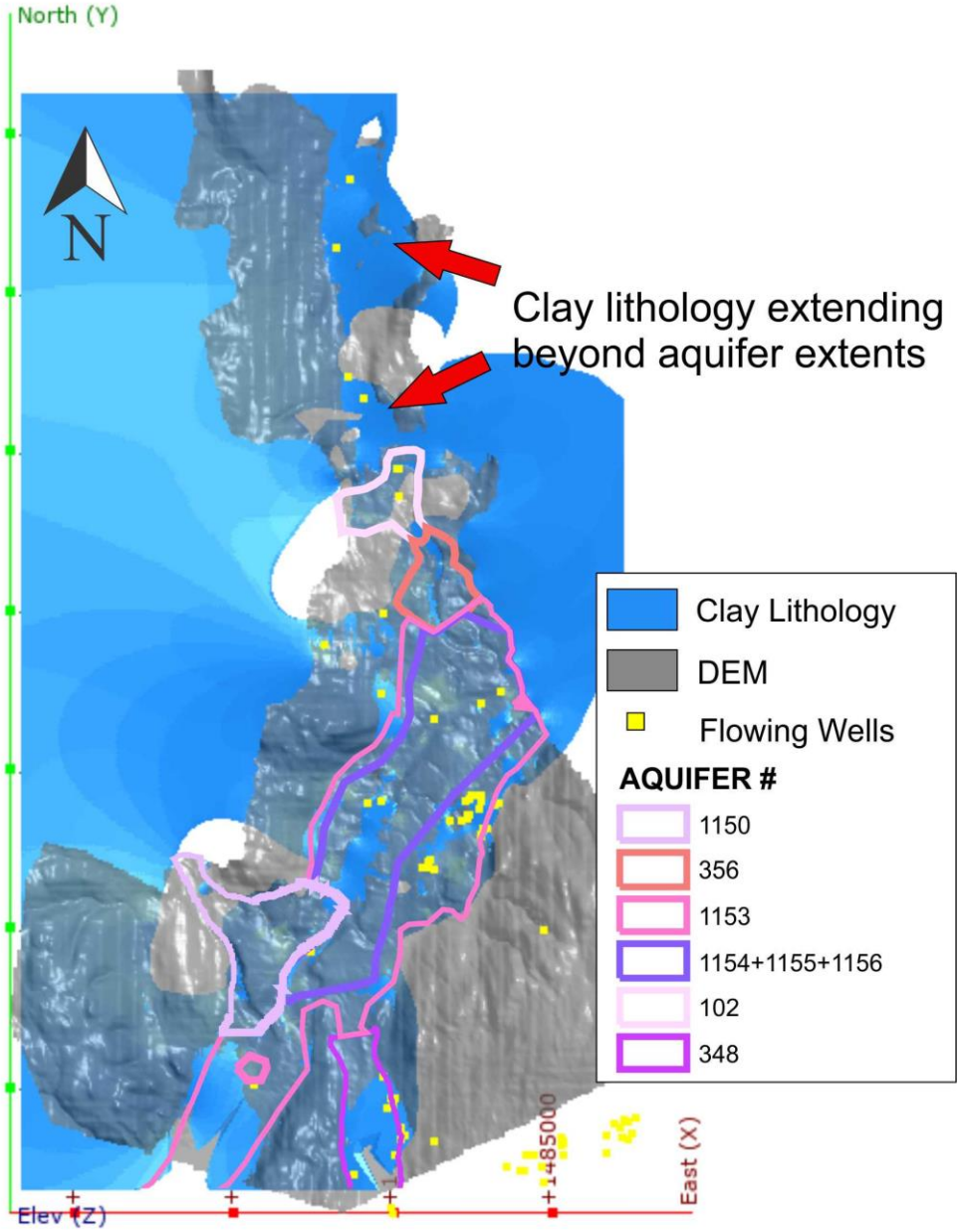

Figure 5.5 The DEM and the Leapfrog extent of clay in the Armstrong area showing flowing wells in unconsolidated materials and the outlines of the mapped confined aquifers superimposed. Red arrows indicate the extent of the clay unit beyond the confined aquifers.

5.4. Fraser Valley

5.4.1. Aquifers 58 and 33

The Fraser Valley has one Well Drilling Advisory for aquifer the Nicomekl-Serpentine aquifer (Aquifer # 58) in Surrey and Langley (Province of BC, 2018b). The majority of flowing wells in the Fraser Valley occur in this aquifer with 183 flowing wells correlated to the aquifer (Province of British Columbia, 2021). Aquifer 58 is a deep (60 – 150 mbgs) confined sand and gravel aquifer, with a median water depth of 3.05 mbgs (Province of British Columbia, 2016) and a median well depth of 79.25 mbgs (Province of British Columbia, 2020b). The advisory uses the extent of Aquifer 58 as the extent of the flowing well advisory Province of British Columbia, 2018b). Figure 5.6 shows the extent of Aquifer 58 and the unconsolidated flowing wells.

Aquifer 33 (the West of Aldergrove Aquifer) is also a confined sand and gravel aquifer (Figure 5.6). The Province shows 97 flowing wells correlated to the aquifer (Province of British Columbia, 2021a), 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 British Columbia, 2021b). Aquifer 33 is an intertill aquifer with two permeable units that slope westward and merge into a single unit in the west (Province of British Columbia, 2020a).

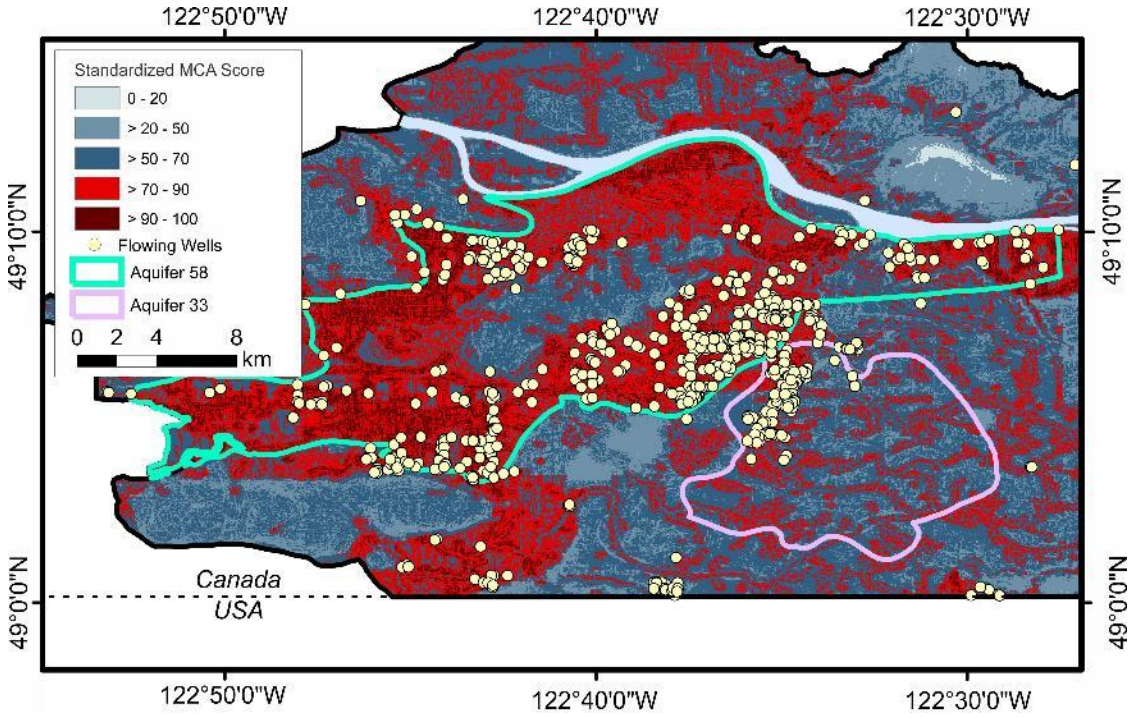

Figure 5.6 Fraser Valley unconsolidated context MCA map results and flowing wells for the area encompassing Aquifer 58 (pale green) and Aquifer 33 (pink).

The MCA results for the Fraser Valley Unconsolidated context (see Figure 4.10) shows high likelihood broadly across the region; however, high likelihood is concentrated in large areas, such as Aquifer 58 (Figure 5.7). The high likelihood areas that flank the outer perimeter of Aquifer 58 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 higher likelihood (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 high likelihood are generally those at low elevation and low slope angle. This highlights the importance of considering multiple factors to determine the extent of flowing artesian conditions.

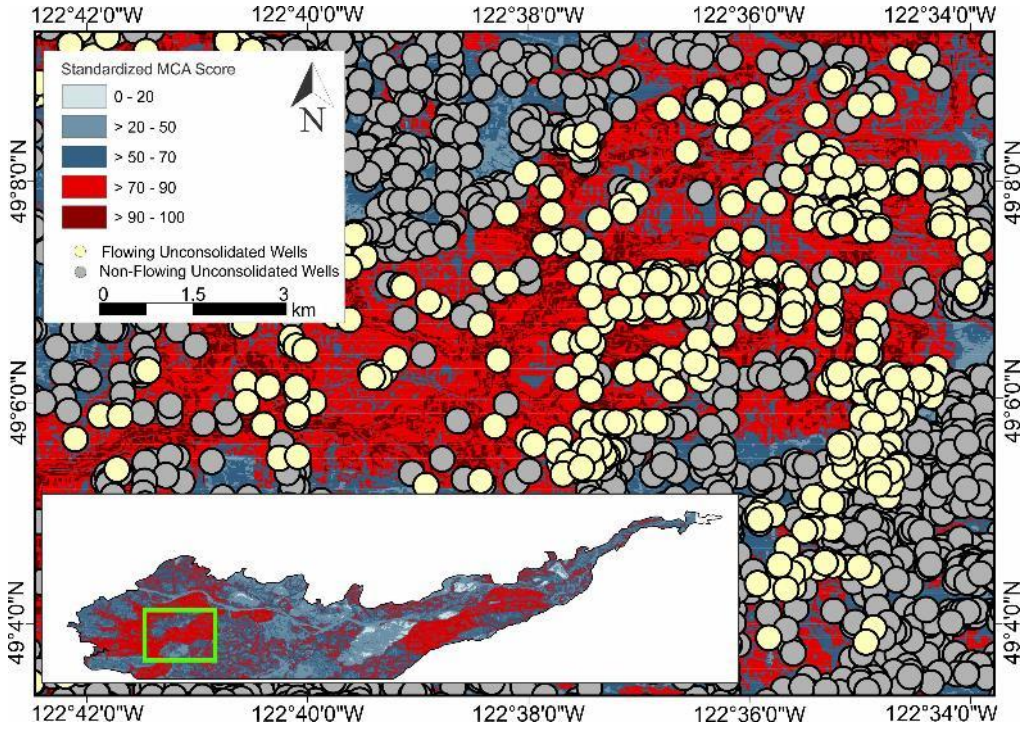

Figure 5.7 Fraser Valley Unconsolidated context MCA map results in a portion of the Nickomekl Valley (from Aquifer 58) showing flowing and non-flowing wells in unconsolidated materials. The inset map shows the extent of the map in the Fraser Valley (green rectangle).

Flowing wells in Aquifer 33 are limited to the western extent of the aquifer (Figure 5.6). The majority of Aquifer 33 is not mapped as high likelihood (i.e. blue cells); however, the western portion is mapped as higher likelihood (albeit 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 higher likelihood area 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 some topographic control on the flowing artesian conditions. The occurrence of flowing wells in this aquifer was explored further in Leapfrog modelling (section 5.5.2).

5.4.2. Aquifer 33 Leapfrog Model

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 data was used to construct the model. A total of 48 wells were used to complete five transects across the aquifer. The two SW to NE transects were comprised only of flowing wells and the three NW to SE transects were compromised of non-flowing wells. The same standardized lithology database previously used in for the Armstrong model was used for this model, and the lithologies were reclassified to clay, glacial, sand, gravel and overburden. Like in 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 intertill 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 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 5.8). 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 5.8b).

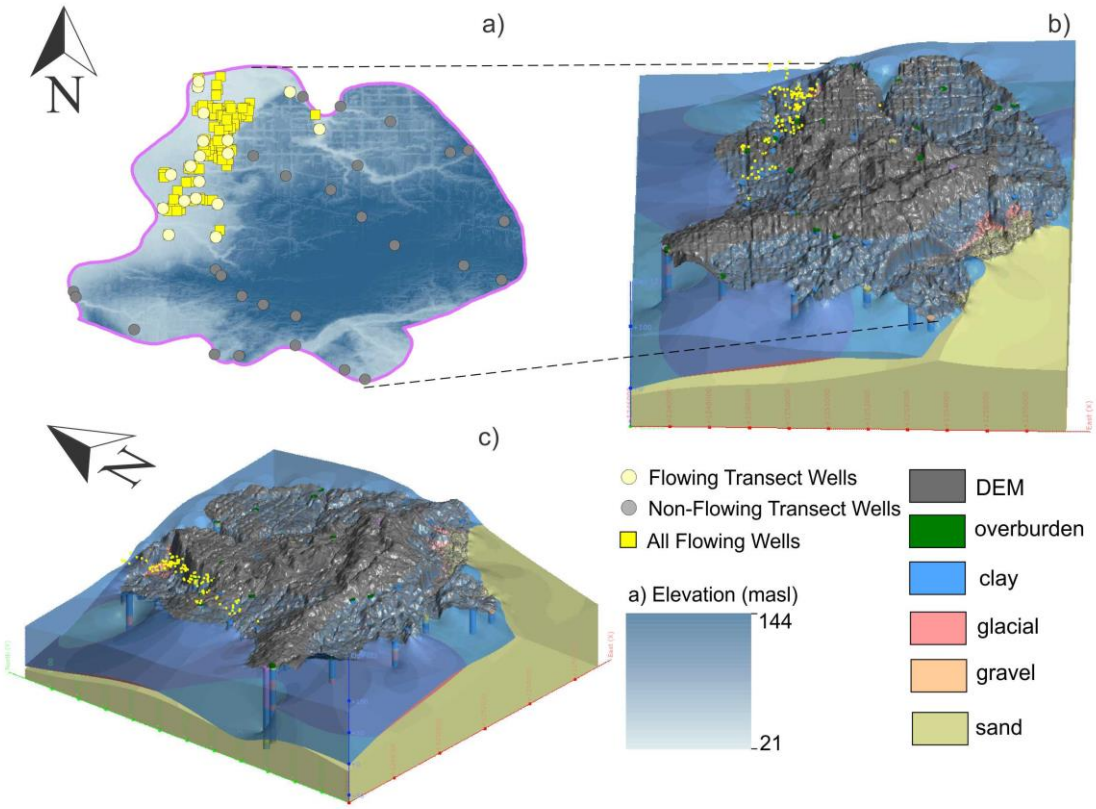

Figure 5.8 a) DEM of Aquifer 33 with the flowing and non-flowing wells used in the transects (circles) and all flowing wells in the aquifer (squares). b) Leagfrog Geo Model for Aquifer 33 DEM overlay c) Leapfrog model for Aquifer 33 re-oriented.

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 but flowing artesian conditions do not occur until there is a drop in elevation. 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 influenced by both the geologically controlled and topography controlled models.

A Well Drilling Advisory for Aquifer 33 is recommended, but highlighting the western portion of the aquifer where there is a change in topography results in flowing artesian conditions.

Chapter 6. Conclusions

The purpose of this research was to determine the likely areas and extent of flowing artesian conditions in the Okanagan Basin and Fraser Valley. 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 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. Groundwater depletion can be particularly problematic in areas with large farming communities (i.e. the Fraser Valley) and arid regions (i.e. the Okanagan Basin).

The purpose of the research was accomplished by meeting four objectives:

1. Developing a method for mapping the likelihood of occurrence of flowing artesian conditions.

2. Testing the mapping method in a variety of hydrogeologic contexts.

3. Validating the mapping results using quantitative (statistical) and qualitative (conceptual) methods.

4. Demonstrating the importance of considering factors that relate to geologically and topographically controlled models.

This chapter outlines the key findings for each objective, the limitations of the research conducted in this study, as well as recommendations for Well Drilling Advisories.

6.1. Overview of Key Findings

6.1.1. Objective 1

The first objective was to '*Develop a method for mapping the likelihood of occurrence of flowing artesian conditions'*. To meet this objective a novel approach was

used to map the likelihood of flowing artesian conditions in three hydrogeological contexts: Okanagan Bedrock, Okanagan Unconsolidated and Fraser Valley Unconsolidated. Unlike previous studies that used a qualitative approach for determining the weights of each factor, this study used the Wilcoxon Test results to determine the weights, while also giving consideration to both flowing and non-flowing wells.

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. But all of the maps had areas of high likelihood that did not have any (or few) known flowing wells. The absence of flowing wells in these high likelihood areas does not necessarily indicate that the maps are incorrect as flowing wells may just not have been encountered yet.

6.1.2. Objective 2

The second objective was to '*Test the mapping approach in a variety of hydrogeologic contexts*'. The novel AHP approach highlighted the notion that the factors which most influence flowing artesian conditions are not consistent throughout the hydrogeologic contexts. Each hydrogeologic context had different factors that were applicable and determined to be statistically significant in influencing the occurrence of flowing artesian conditions. 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 to bedrock) or a factor would have a higher weight one context relative to another. For example, flow accumulation 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.

The Okanagan Bedrock context had the lowest achieved Wilcoxon Test significance level (Section 4.2.2) 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 in Chapter 5 using the Naramata area as a case study.

The Okanagan Unconsolidated had the highest degree of clustering in high likelihood areas of flowing wells. 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 the high likelihood clusters. This could lead to a false assurance that flowing wells will not occur outside of these higher likelihood areas.

Relative to the Okanagan contexts, the Fraser Valley had larger areas mapped as higher likelihood where few flowing wells occur. Areas with flowing artesian conditions could be present in these higher likelihood 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 higher likelihood 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.

6.1.3. Objective 3

The third objective was to '*Validate the mapping results using quantitative (statistical) and qualitative (conceptual) methods'*. 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 that have a higher likelihood of flowing wells, 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 to occur.

The novel AHP approach also allows for non-flowing wells to be incorporated into the standardization process. Location mapping in MCA generally focuses on where a something does occur rather than where does not. The novel 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. This likely resulted in the desirable validation results as it prevented the MCA results from only mapping where wells occur regardless of whether they are flowing or not.

Site specific investigations of flowing artesian conditions indicate that the MCA maps are able to accurately determine the extent of the likelihood of flowing artesian conditions at local scales. In Vernon Creek, the MCA maps provided a reasonable extent to accompany the Well Drilling Advisory in the area. In Langley, the MCA results better refined where flowing artesian conditions could be encountered in Aquifer 58. The Naramata case study presented a 2D conceptual model demonstrating how flowing and non-flowing bedrock wells can occur immediately adjacent to each other. This validates the more stippled 'higher likelihood' areas in the Okanagan Bedrock MCA map.

6.1.4. Objective 4

The fourth objective was to '*Demonstrate the importance of considering factors that relate to geologically and topographically controlled models'*. The site specific evaluations provided a means to examine whether locations are topography or geologically controlled. While some locations, such as Naramata, seems to be predominately geologically controlled, an important conclusion is that most case studies had factors that indicate both geologically and topography controlled models have influence. The case studies highlight the importance of a confining unit. All of the case studies have some variation of a confining unit, but flowing wells occur sporadically

outside of locations with confining units. This indicates that confining units are not a determining factor but a highly influential one. However, the majority of the case studies have topography that mirrors the conditions for a topography controlled model. While a drop in elevation is needed in both models to result in a potentiometric surface above ground surface, the site specific examinations indicate that topography likely plays a determining role in the occurrence of flowing wells. The majority of clusters of flowing wells occur in valley bottoms in both a regional and smaller scale. Vernon Creek, for example, has topography that mirrors that of the topography controlled model but also has the majority of flowing wells drilled into a confined aquifer. This highlights the concept presented by Toth (1963) in chapter 1 that topography still has an influence on groundwater flow paths when a confining unit is present.

Lastly, the MCA maps were able to predict wells that occurred more sporadically outside of confining units. These wells may represent locations where the topography controlled model is more influential. Not mapping the presence of the confining units factor as a Boolean term allows for these wells to be captured in the MCA mapping.

6.2. 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 potential limitations in this study.

The first 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 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 second 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 lower 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 has having the lowest achieved significance level in the final round of Wilcoxon Testing (Table 4.2)

A third limitation is that the approach used in this study only considered the flowing well dataset for standardization, and thus did not include the non-flowing wells in the standardization. Adding the non-flowing wells into the standardization process may result in fewer areas being mapped as high likelihood. For example, the high likelihood in the Fraser Valley Unconsolidated context in the east where few flowing wells occur may be reduced if the standardization process included non-flowing wells. This approach, however, could be detrimental in study areas like the Okanagan Bedrock context where flowing and non-flowing wells frequently occur in close proximity to each other.

Importantly, the map scores are not a direct representation of likelihood because the highest percent frequencies and the highest positive difference (flowing > non-flowing) between percent frequencies do not correlate with the highest standardized MCA scores. Ideally, the highest MCA score would be associated with the highest percent frequency of flowing wells (i.e. the highest likelihood) and the decrease in percent frequency would directly correlate with the decrease in likelihood. This is not the case in any of the hydrogeologic contexts (Figure 4.1 and 4.2). In the Fraser Valley Unconsolidated context and the Okanagan Unconsolidated context the highest standardized MCA scores (90 – 100 binned interval) have the lowest percent frequencies in the ‘more likely than not’ classification. In the ‘more likely than not’

classification, flowing wells occur with greater percent frequencies than non-flowing wells and have the largest difference in percent frequencies. Additionally, the Okanagan Bedrock context has some of the lowest percent frequencies of flowing (and non-flowing) wells in the 90 – 100 binned interval (Figures 4.1 and 4.2).

Lastly, these methods are 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.

6.2.1. Mitigating the General Limitations of MCA

Chapter 1 in this thesis highlighted four general limitations of using MCA (Section 1.3.3.) as outlined by Thakkar (2021). These limitations were mitigated in the thesis to provide more accurate results. The following addresses how each of these limitations applied (or did not apply) to the thesis, with particular emphasis on how the novel approach was able to mitigate these limitations.

5. *Difficulty in structuring an appropriate hierarchy will lead to a faulty selection or prioritization of the alternatives.*

This limitation is not generally applicable to this research. In a GIS environment the decision alternatives refer to an action (what to do?) and location (where to do it) (Malczewski & Rinner, 2015). In the context of this research there is no action implicit in the MCA mapping, and in regard to mapping, flowing artesian conditions should either exist or not exist - the location of flowing artesian conditions does not depend on a

decision (hence why the term *Multi-Criteria Analysis* is preferred over other popular options such as *Multi-Criteria Decision Analysis*). Alternatives for this research could potentially refer to a series of maps, each of which could provide an estimate for flowing artesian conditions for a single hydrogeologic context. However, the structuring of the hierarchy in this research was undertaken systematically and quantitatively through the novel approach using the AHP, reducing the possibility for alternatives. The only potential alternatives presented in this thesis were in the sensitivity analysis presented in Appendix D, which concluded that the maps were not sensitive to the variations in bin sizes.

6. *Primarily governed by subjective opinions of the experts and their intuitions, and hence bias in the judgment and inconsistency limits the acceptability of MCA results.*

This limitation stems from the fact that AHP is traditionally a qualitative approach based on ranking the preferences of a decision maker (Saaty, 1987). Determining which factors have the greatest influence in determining where flowing artesian factors exist is critical in accurately mapping the extent of flowing artesian conditions. A novel approach was used in this thesis add a quantitative aspect to the AHP by ranking the factors based on the highest achieved significance level the factor achieved.

7. *Difficulty in validating the results with the alternate MCA technique as the key properties and steps followed by various MCA techniques are different. This limits the generalization of the results.*

One of the major criticisms of MCA is that different techniques may produce different results when applied to the same problem because of the various strengths, weaknesses, and considerations given by each technique (Thakkar, 2021). This limitation was not directly able to be mitigated in the thesis; however, the incorporation of a statistical component (through the novel AHP approach) as well as the statistical validation of the MCA maps provided validation of the results without the need for testing against an alternative technique.

8. *The criteria and alternatives are dynamic in nature for a real-life problem and hence the priorities or ranking generated by MCA technique may not remain valid*

for a longer-period time and hence it is advisable to support the results of MCA with a detailed sensitivity analysis.

This limitation refers to subjective options of decision makers. In the context of this research the criteria/alternatives themselves are not dynamic. The criteria refer to the factors that influence of the location of flowing artesian conditions and these factors are constant. For example, slope will always be a factor that influences flowing artesian conditions, and how significant that influence is will vary from location to location, but its applicability does not change. Factors may be considered dynamic in the sense that they can change over time; however, this is unlikely to change on a timescale relevant to the mapping. Slope instability and the resulting changes in slope from this instability is one example of how the factors are dynamic. This highlights how landscapes are dynamic in nature, but it is unlikely that factors will change significantly enough over a relevant timeframe and spatial extent.

As addressed previously, the concept of alternatives applied to the majority of MCA research is not widely applicable to the context of this thesis. However, flowing artesian conditions are not static over time, but can fluctuate seasonally with groundwater levels that respond to varying recharge rates (e.g. influx from spring freshet) and with longer term groundwater fluctuations as well (e.g. groundwater depletion from over consumption).

6.2.2. Influential Factors

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 is likely one of the most important factors, with lower slopes having the highest occurrence in the Unconsolidated contexts and moderate slopes having the highest occurrence 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 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.

6.3. Recommendations for Well Drilling Advisories

Throughout the Fraser Valley and Okanagan Basin there is potential for the developing additional Well Drilling Advisories. Specifically, the regions of Naramata and Armstrong would benefit from advisories. While it is generally easier to control flow in bedrock when drilling into flowing artesian conditions (Province of BC, n.d.) the high variability in in the extent of flowing artesian conditions in Naramata could lead to a sense of false sense of security that flowing artesian conditions will not be encountered. Additionally, 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. The MCA results could further refine the extent of the flowing wells in the Well Drilling Advisory for Surrey and Langley (Aquifer 58) to exclude the highlands between the two river valleys. This advisory could also potentially be modified to include Aquifer 33 as the flowing wells are in the immediate vicinity.

6.4. Potential Uses for the MCA Maps

The maps developed in this thesis 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 to occur and to recommend Well Drilling Advisories as appropriate in those areas, but there are several other potential uses for the maps.

6.4.1. Well Drilling Advisories

Firstly, Well Drilling Advisories do not need to be limited to those recommended in this thesis. This thesis focused on specific areas that are representative of high likelihood areas in each hydrogeologic context. However, areas mapped as high likelihood occur in each hydrogeologic context in other areas, and these warrant more detailed examination.

6.4.2. 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 high likelihood (or is adjacent to a higher likelihood area), 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 6.2). The maps are simply meant as one tool to aid in the decision making process. Below are several scenarios and suggestions for how drillers may interpret the results.

Scenario 1

A drilling site is identified on the map and found to be situated in an area with mostly red cells. The area is also found to have a high occurrence of flowing wells. In this case a driller can assume that it is likely that flowing artesian conditions will be encountered during drilling and should prepare adequately.

Scenario 2

A drilling site is identified on the map and found to be in an area with a moderate number of red cells, intermixed with blue cells. The area is found to have a low

occurrence of flowing wells, but there is also a low occurrence of non-flowing wells. In this case a driller may choose to proceed cautiously as flowing artesian conditions may be encountered.

Scenario 3

A drilling site is identified on the map and found to be in an area with mostly blue cells. The area is also found to have a low occurrence of flowing wells. In this case a driller may assume that there is low potential for encountering flowing artesian conditions.

The statistics 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.

6.4.3. Drilling Authorizations

Under the *Water Sustainability Act* new wells that are drilled for non-domestic use must have a well license. Groundwater licenses are administered by the BC Ministry of Forests, Lands, Natural Resources Operations and Rural Development. These maps could be used to help inform drilling authorization decisions in these areas.

6.4.4. Future Mapping

The methods developed for mapping the likelihood of encountering flowing wells can be applied in 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.

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Appendix A: Full Size Fraser Valley and Okanagan Basin Figures

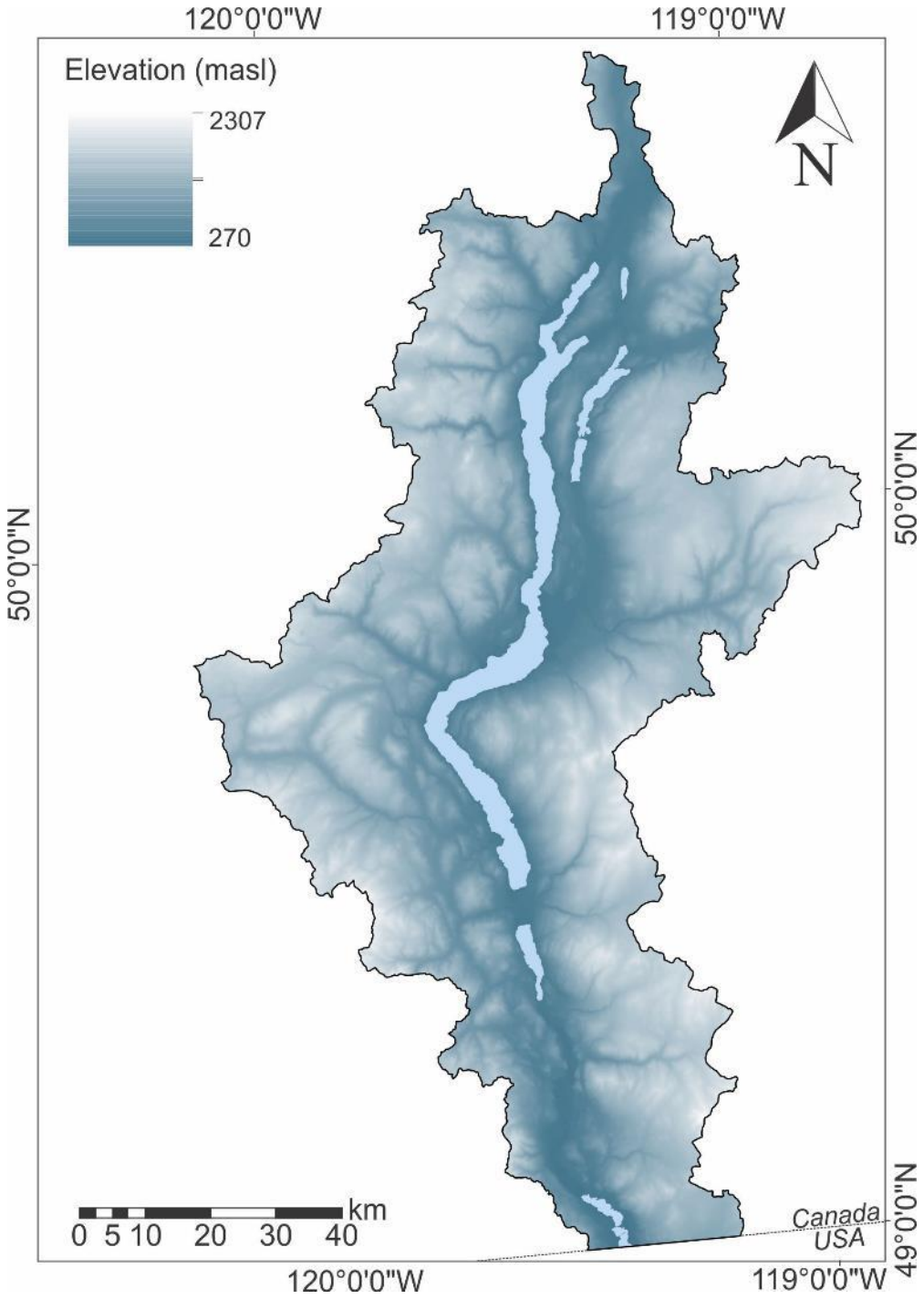

Figure A.1 Okanagan DEM.

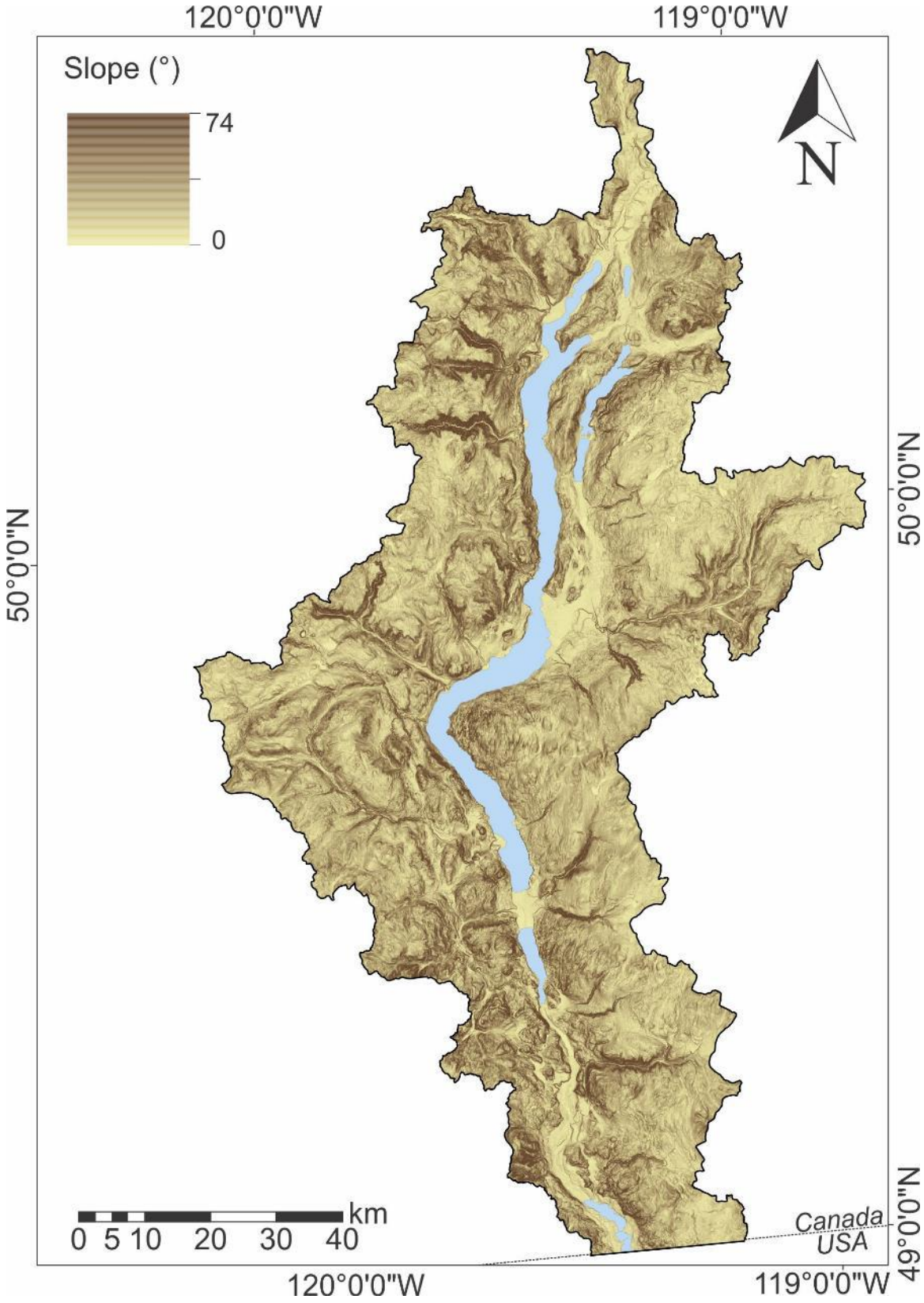

Figure A.2 Okanagan slope.

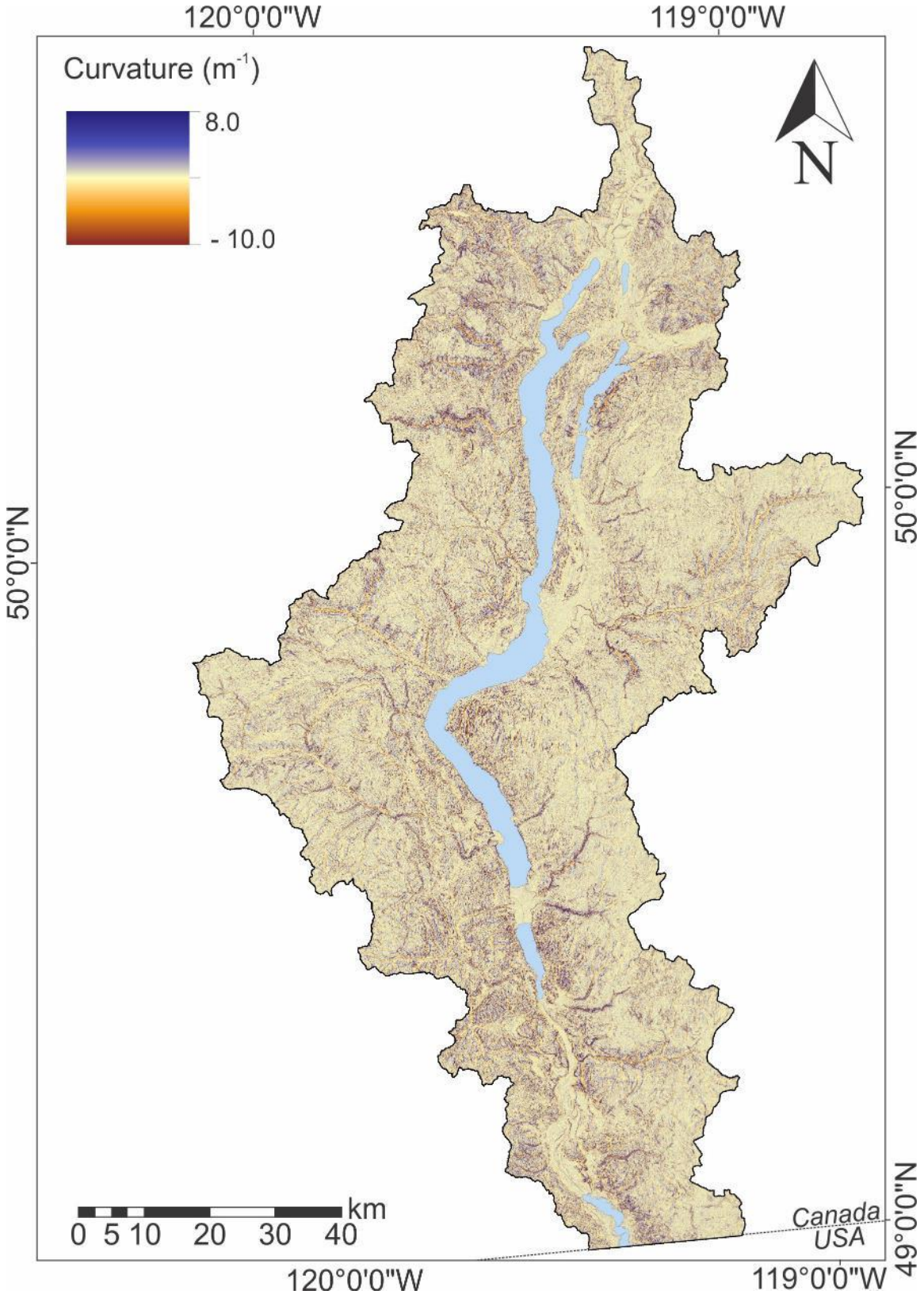

Figure A.3 Okanagan curvature.

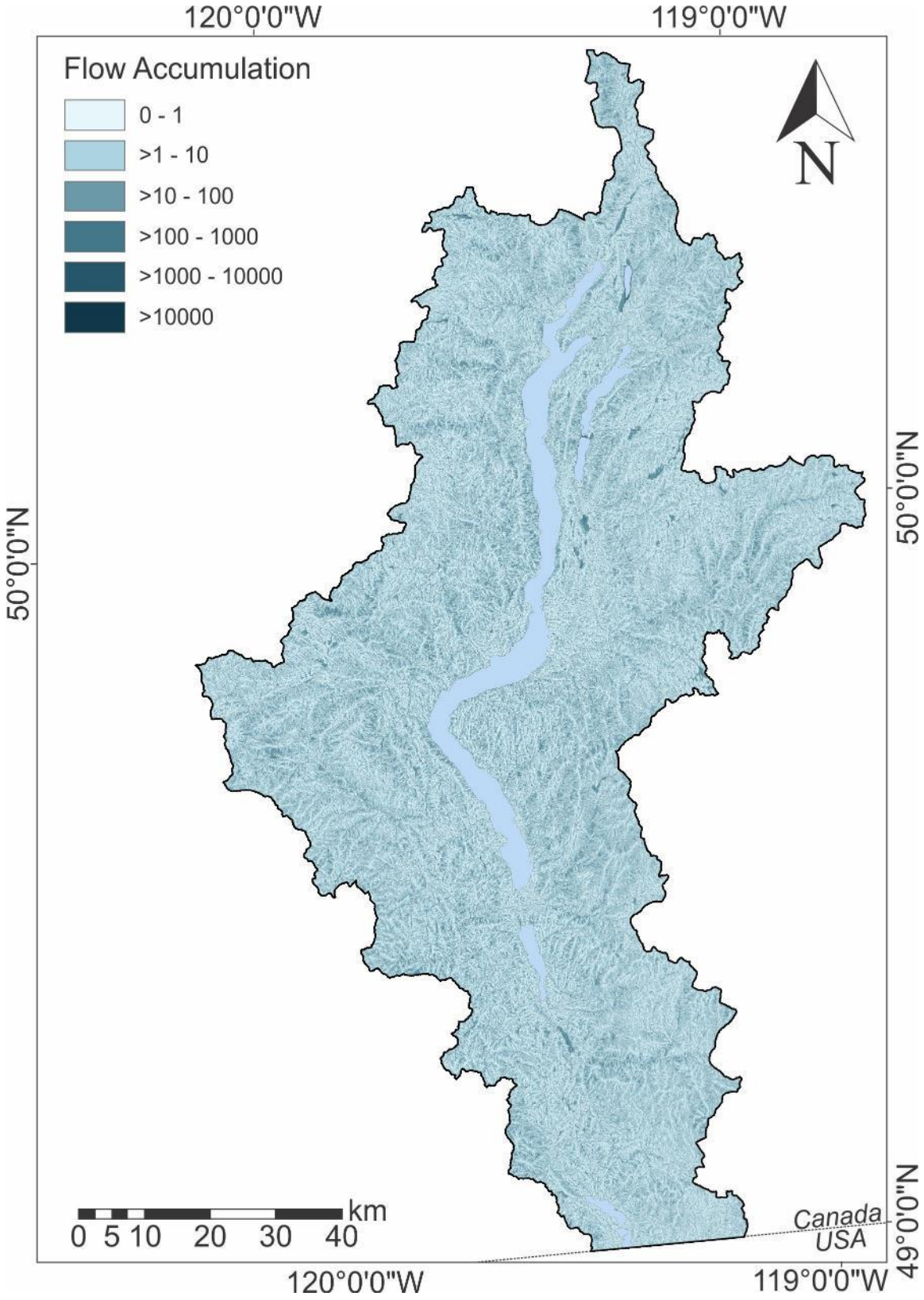

Figure A.4 Okanagan flow accumulation.

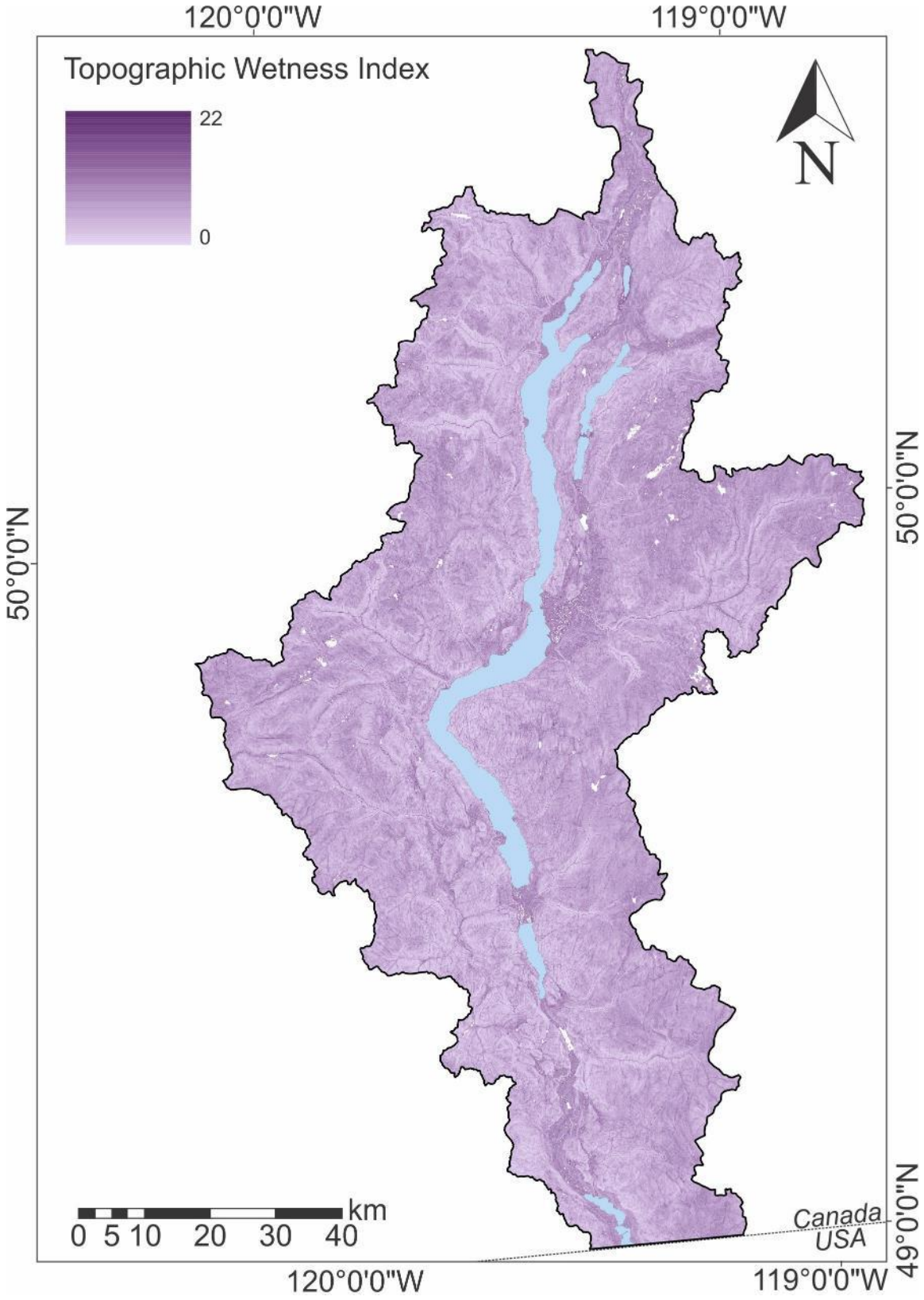

Figure A.5 Okanagan topographic wetness index.

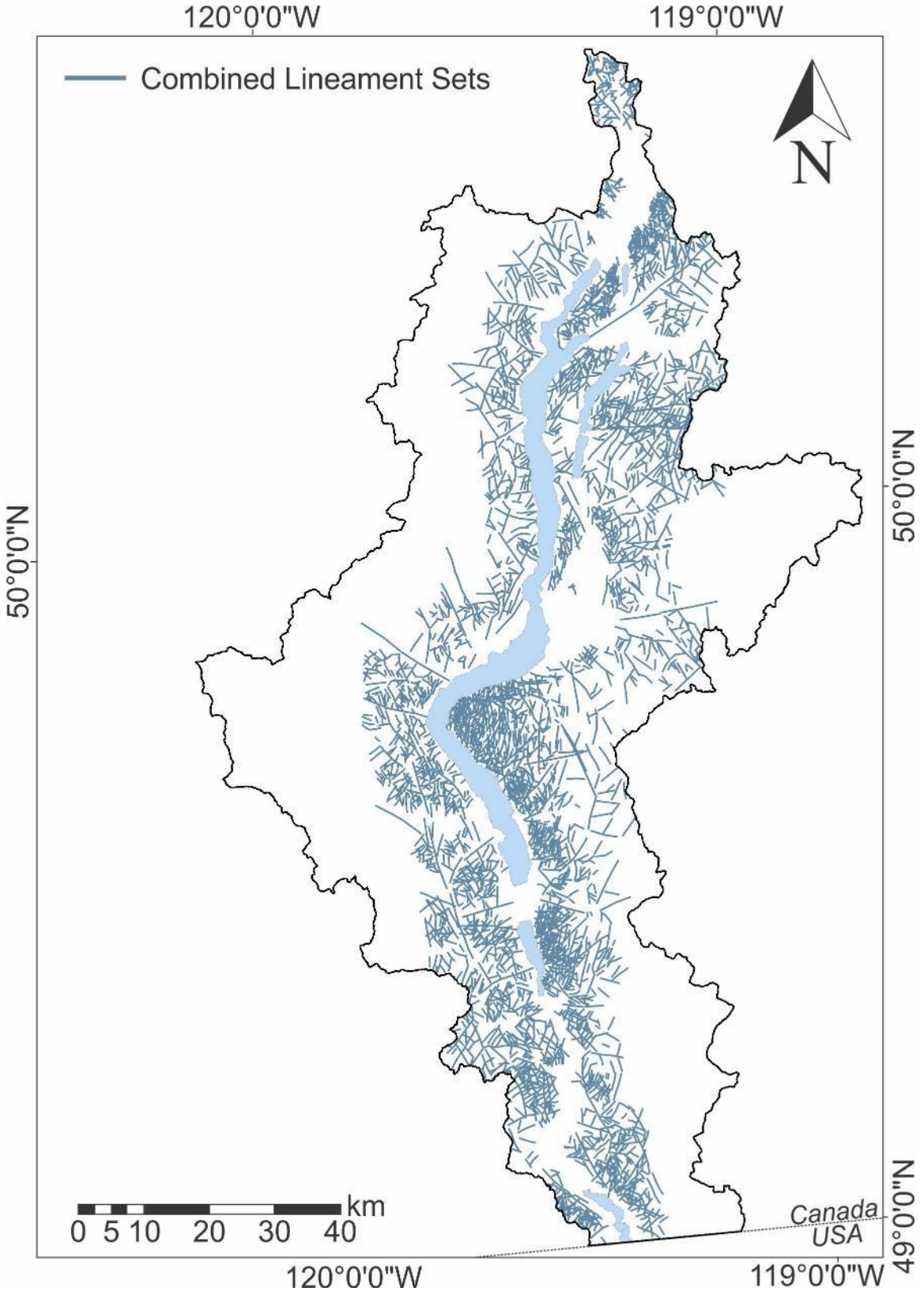

Figure A.6 Okanagan Lineament sets combined.

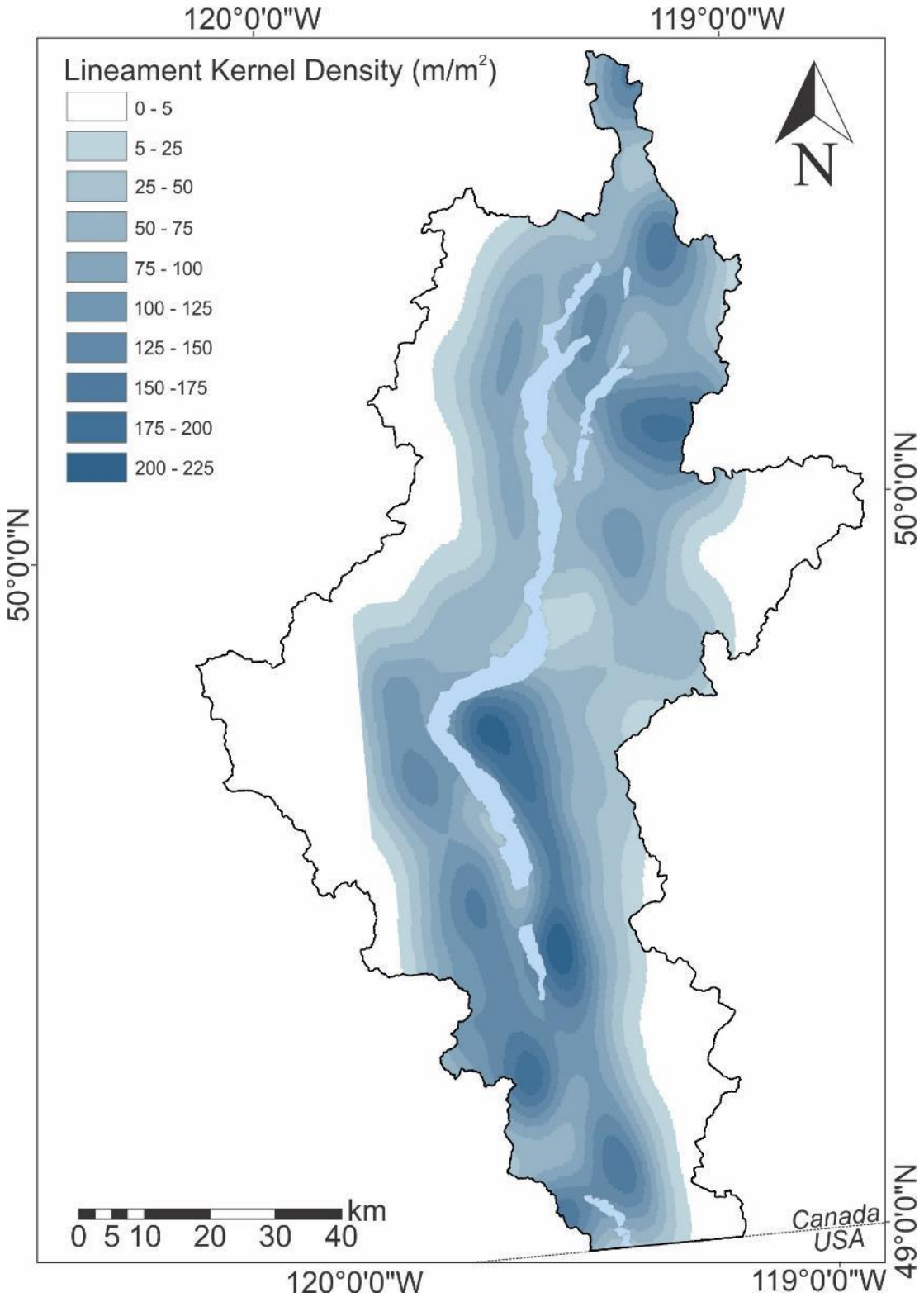

Figure A.7 Okanagan lineament kernel densities for all sets combined.

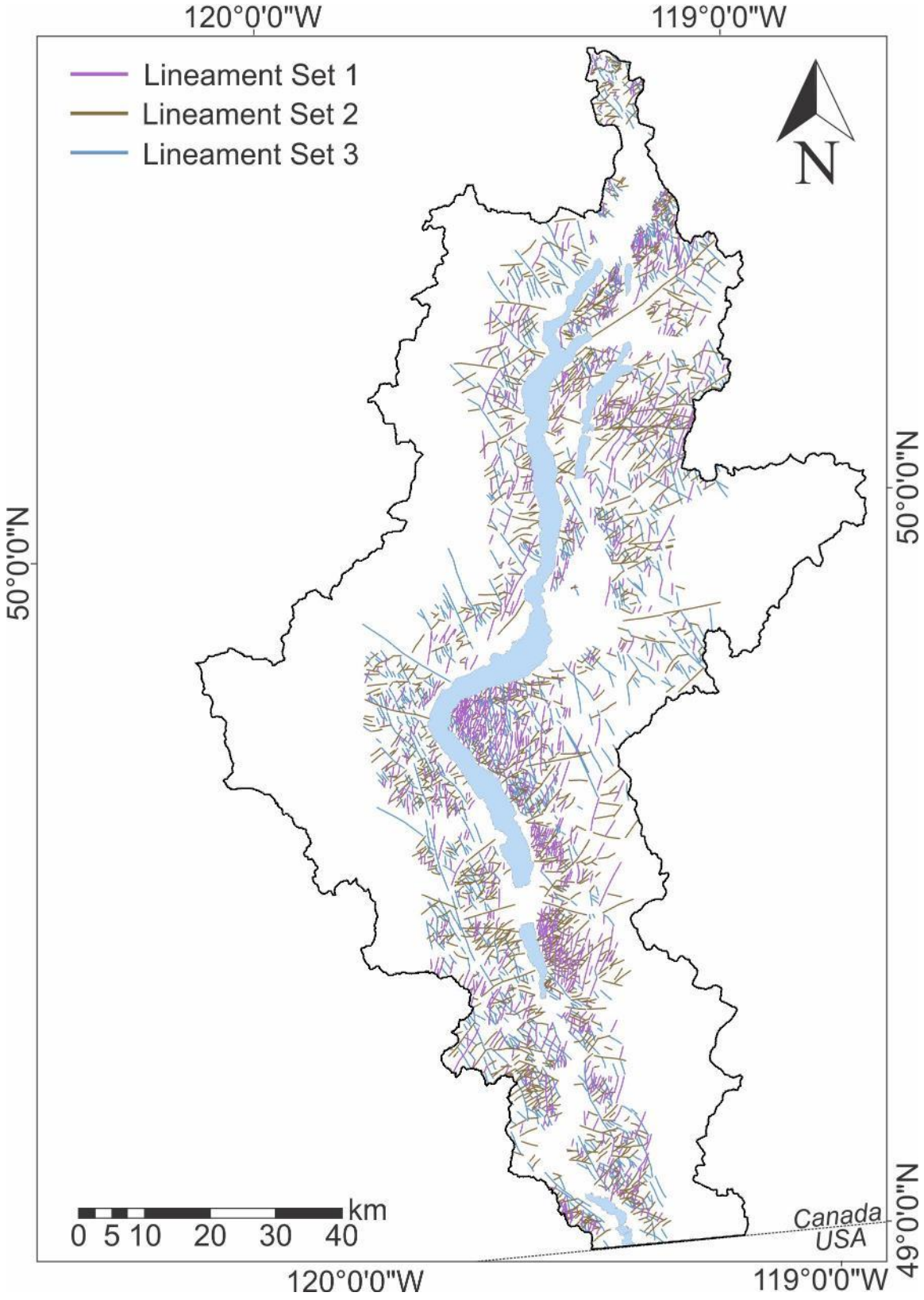

Figure A.8 Okanagan lineaments sets.

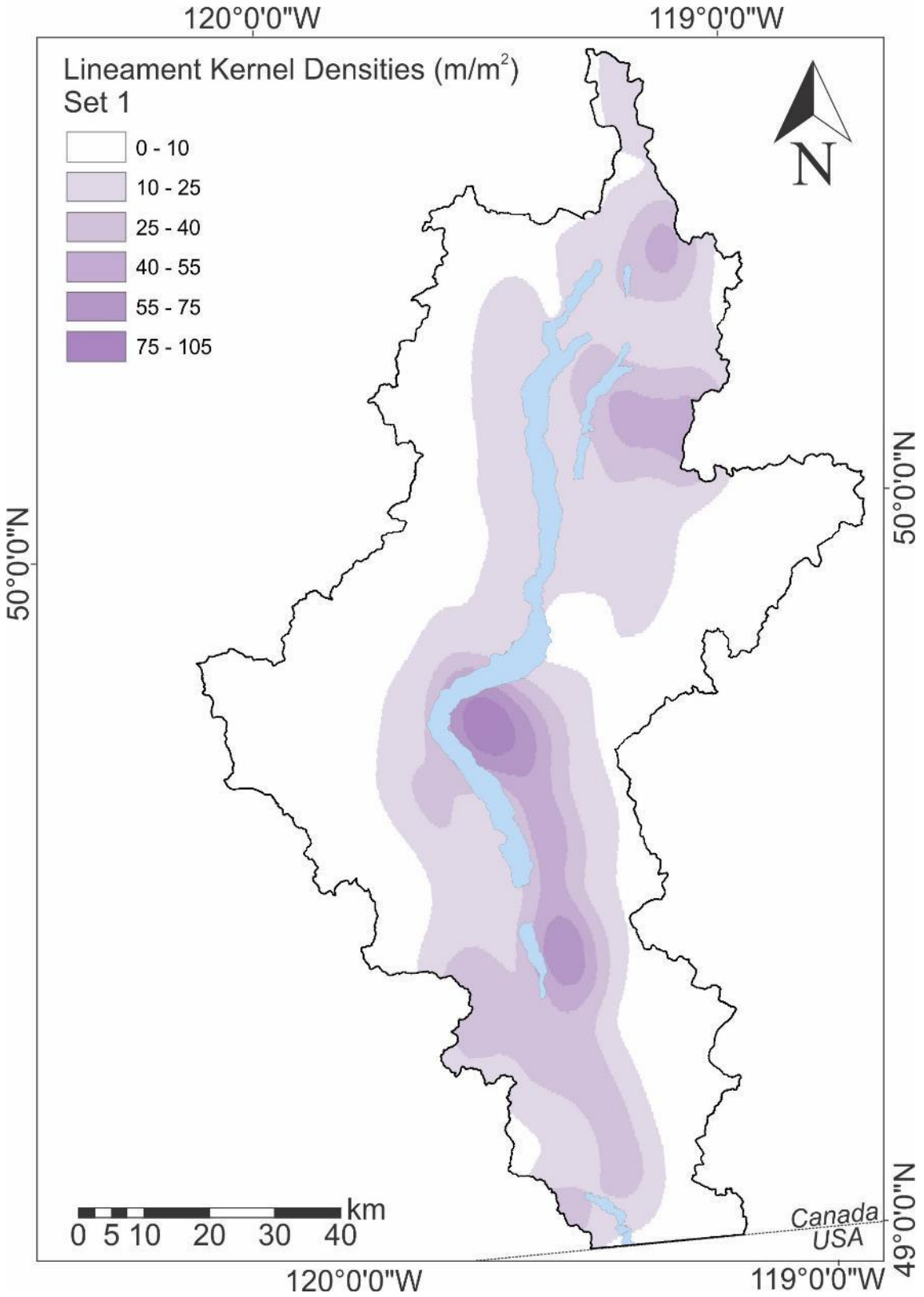

Figure A.9 Okanagan lineament kernel densities set 1.

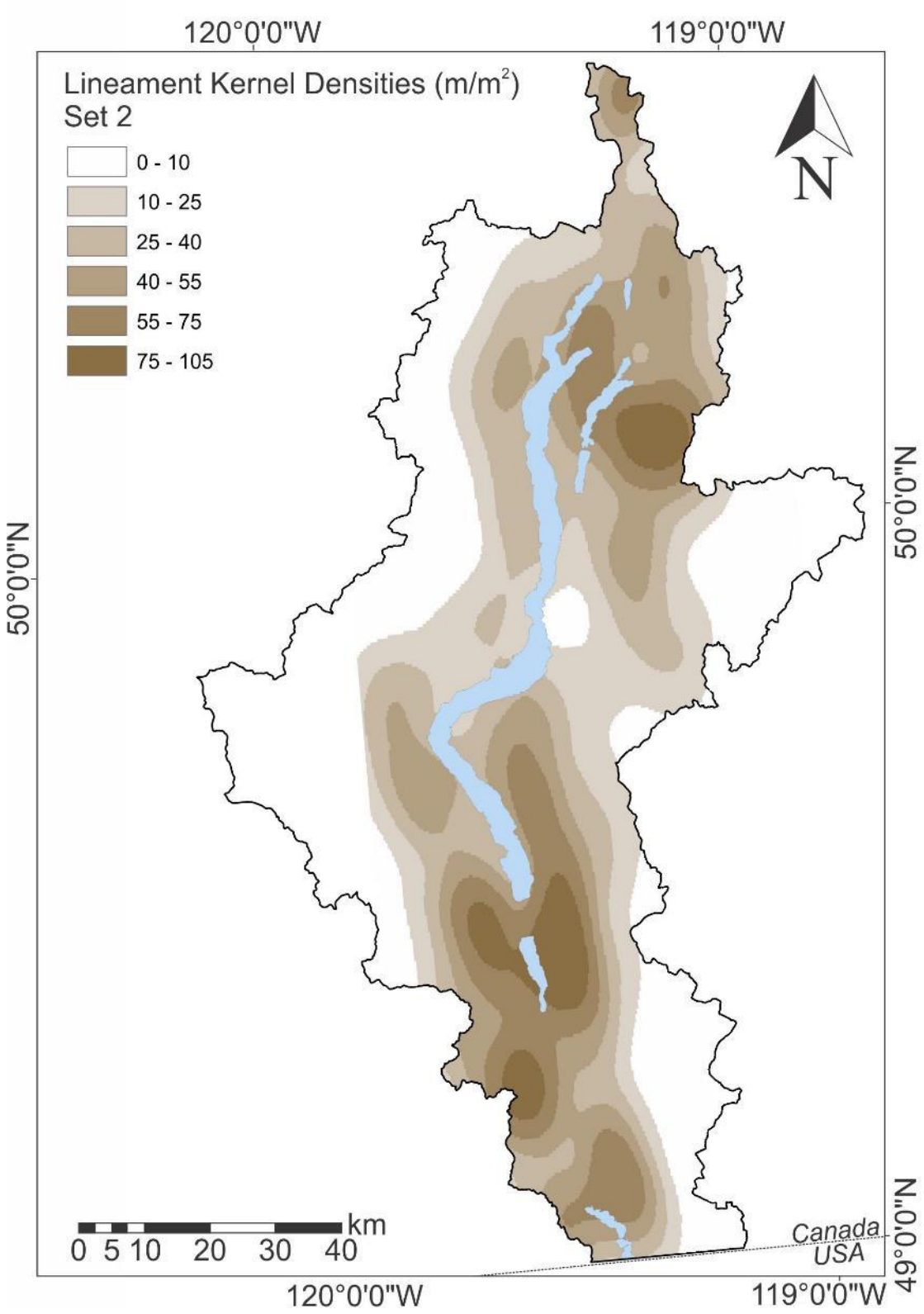

Figure A.10 Lineaments kernel densities set 2.

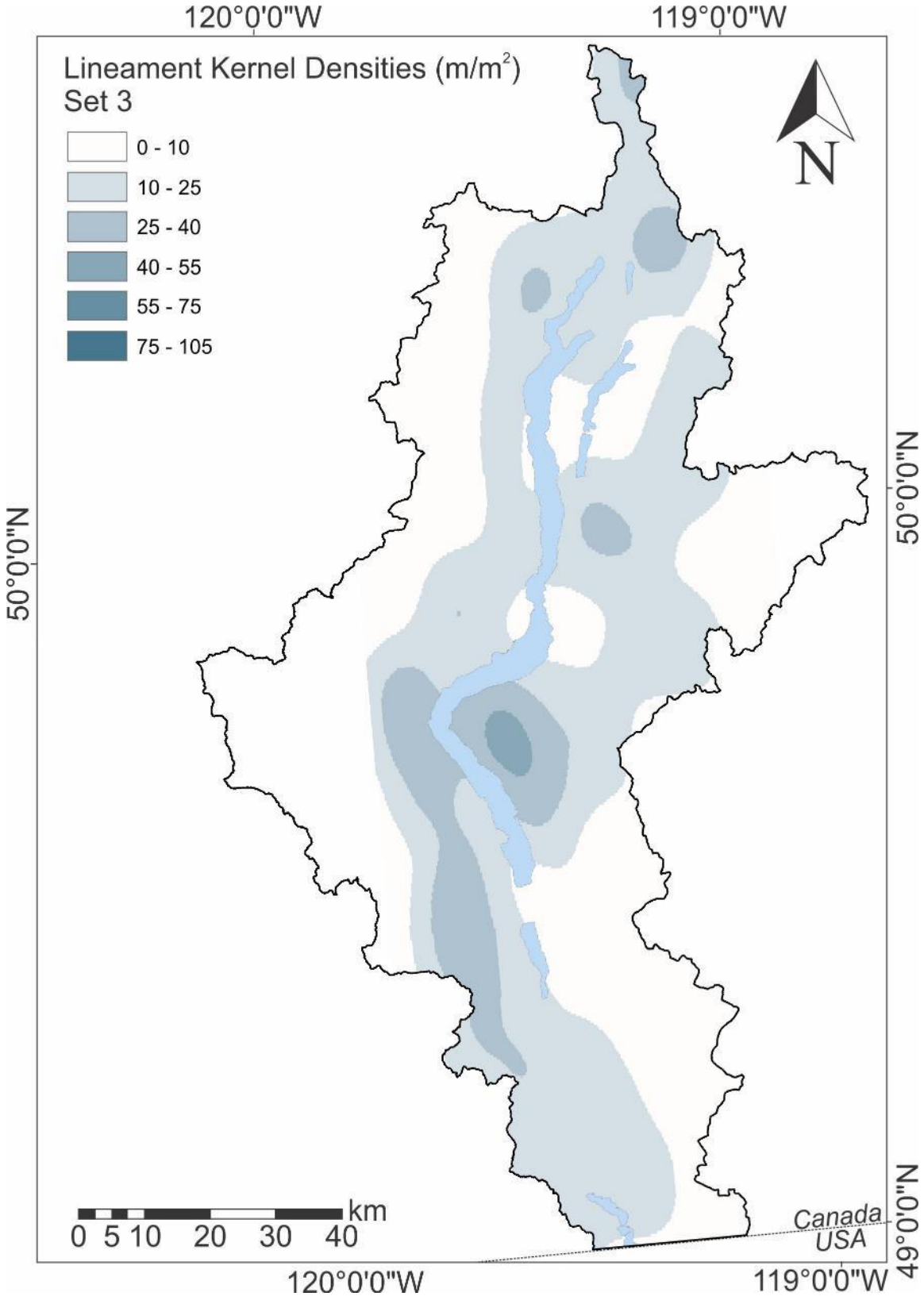

Figure A.11 Okanagan lineament set 3.

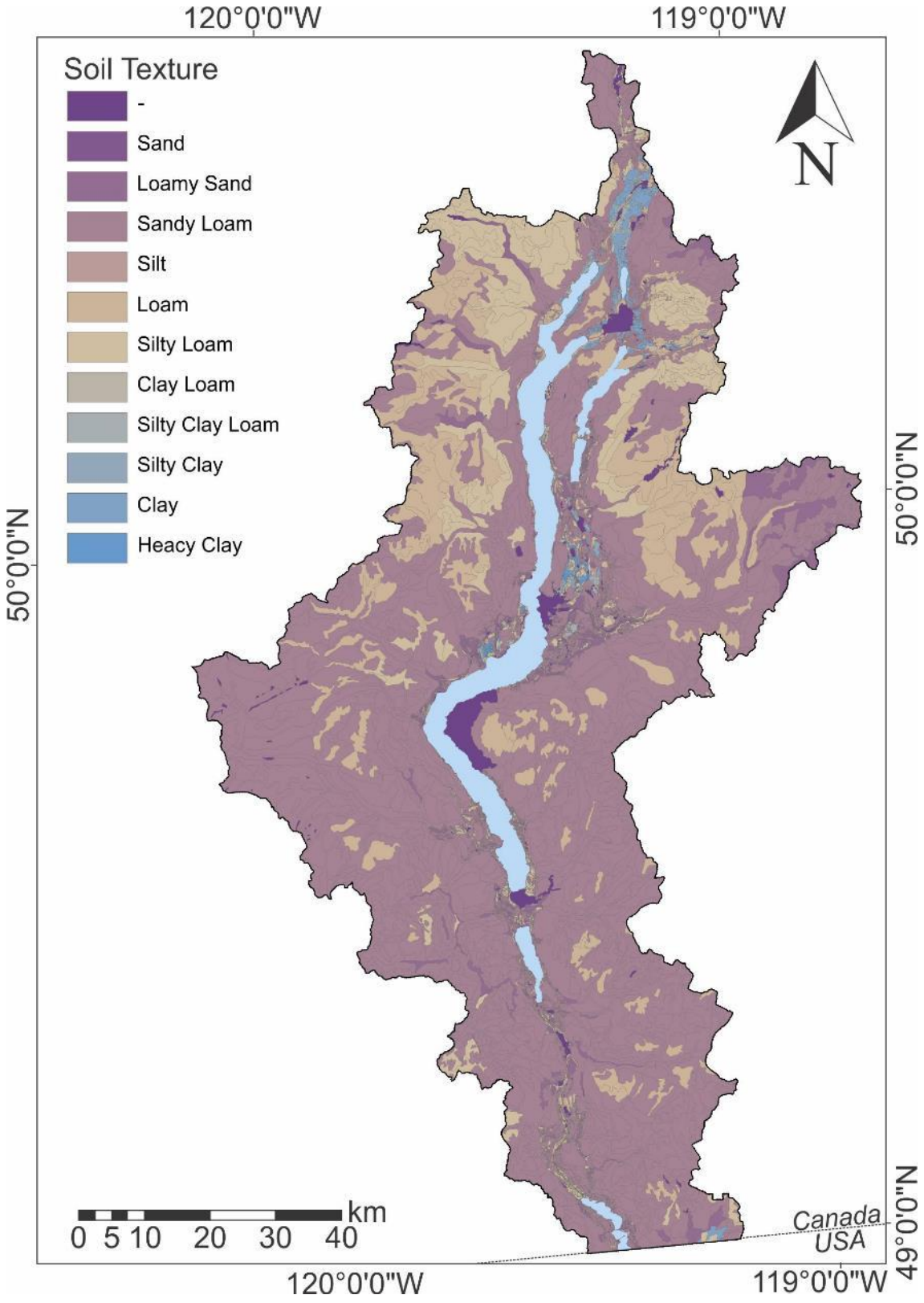

Figure A.12 Okanagan soil texture.

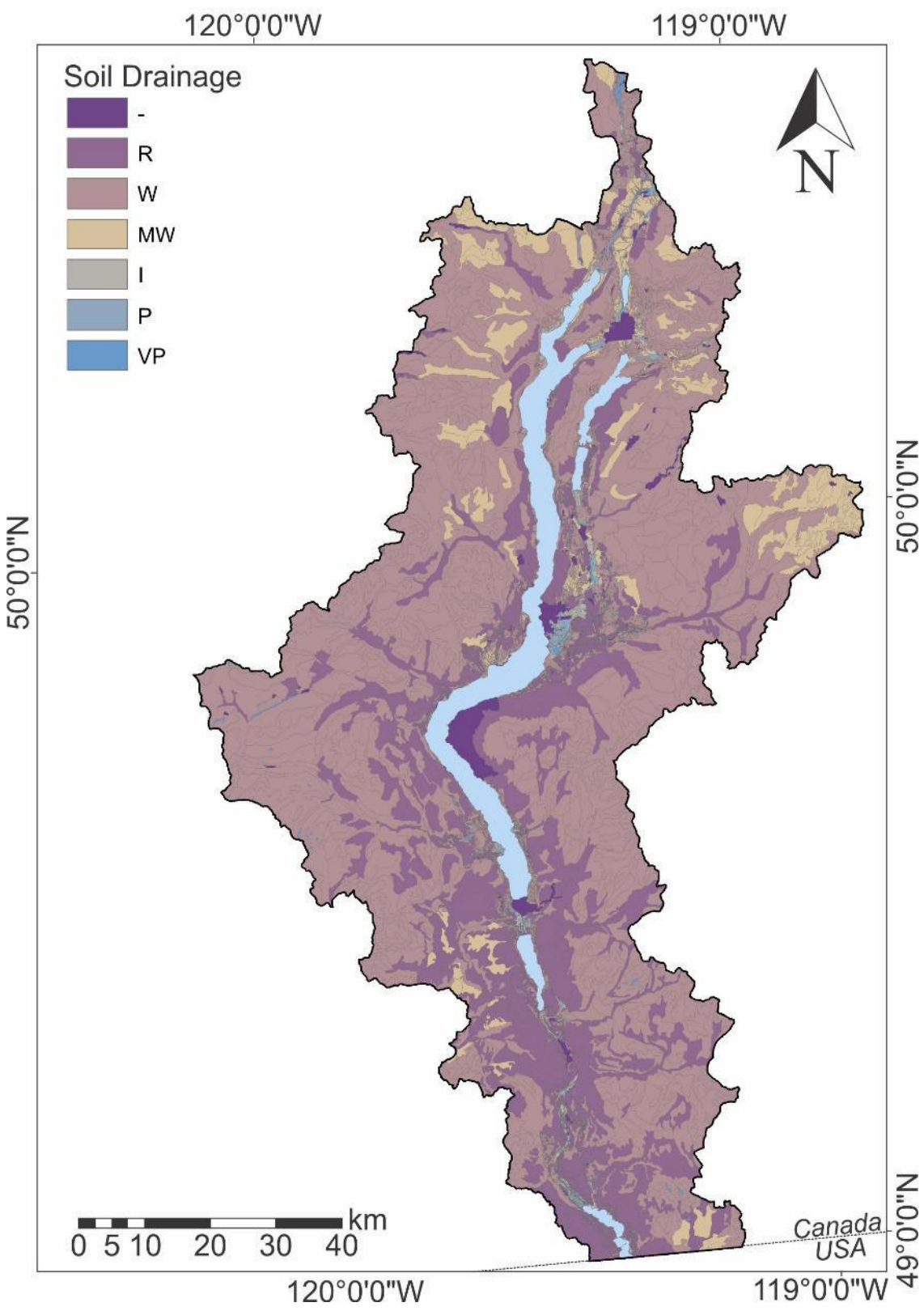

Figure A.13 Okanagan soil drainage.

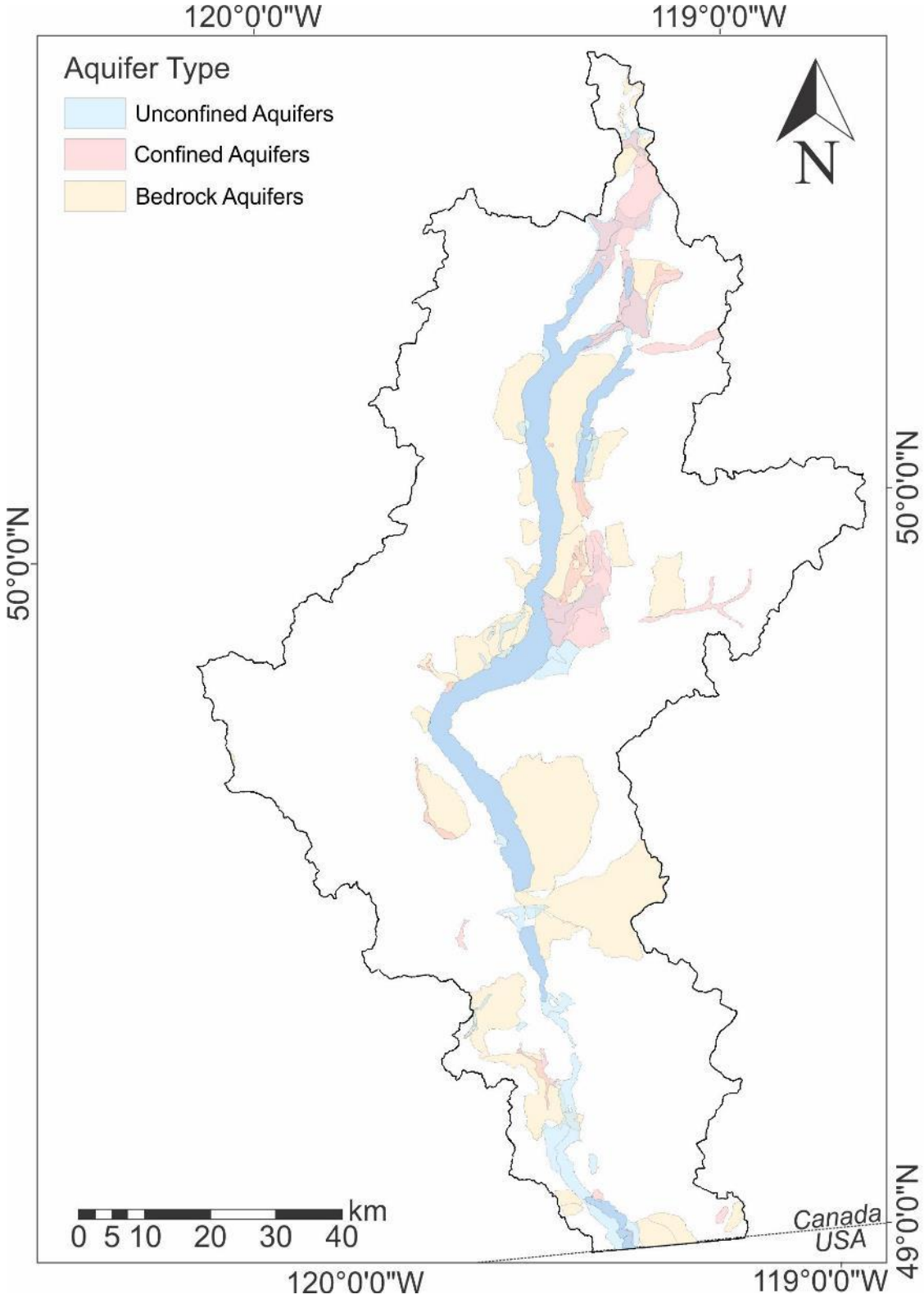

Figure A.14 Okanagan aquifers.

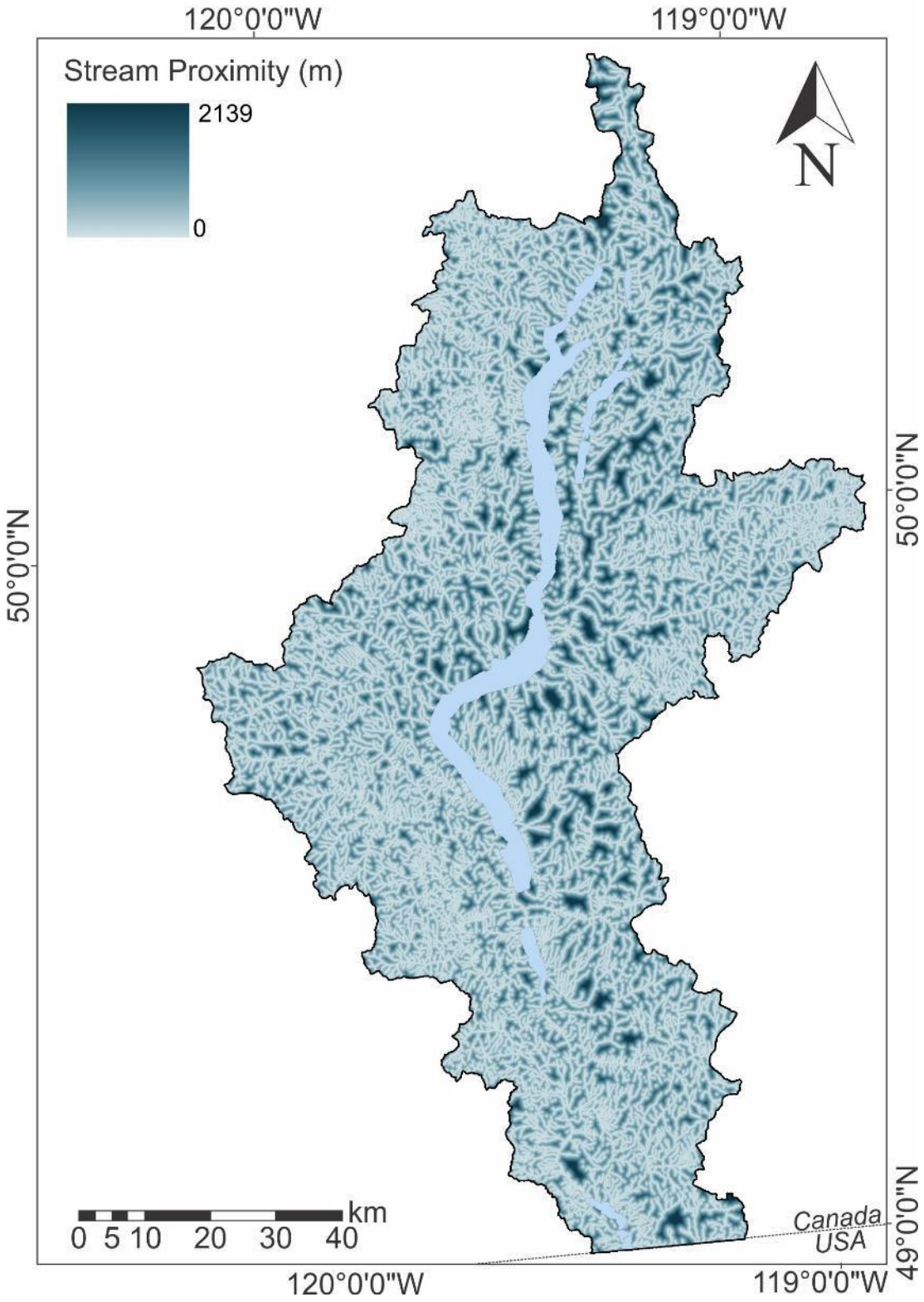

Figure A.15 Okanagan stream proximity.

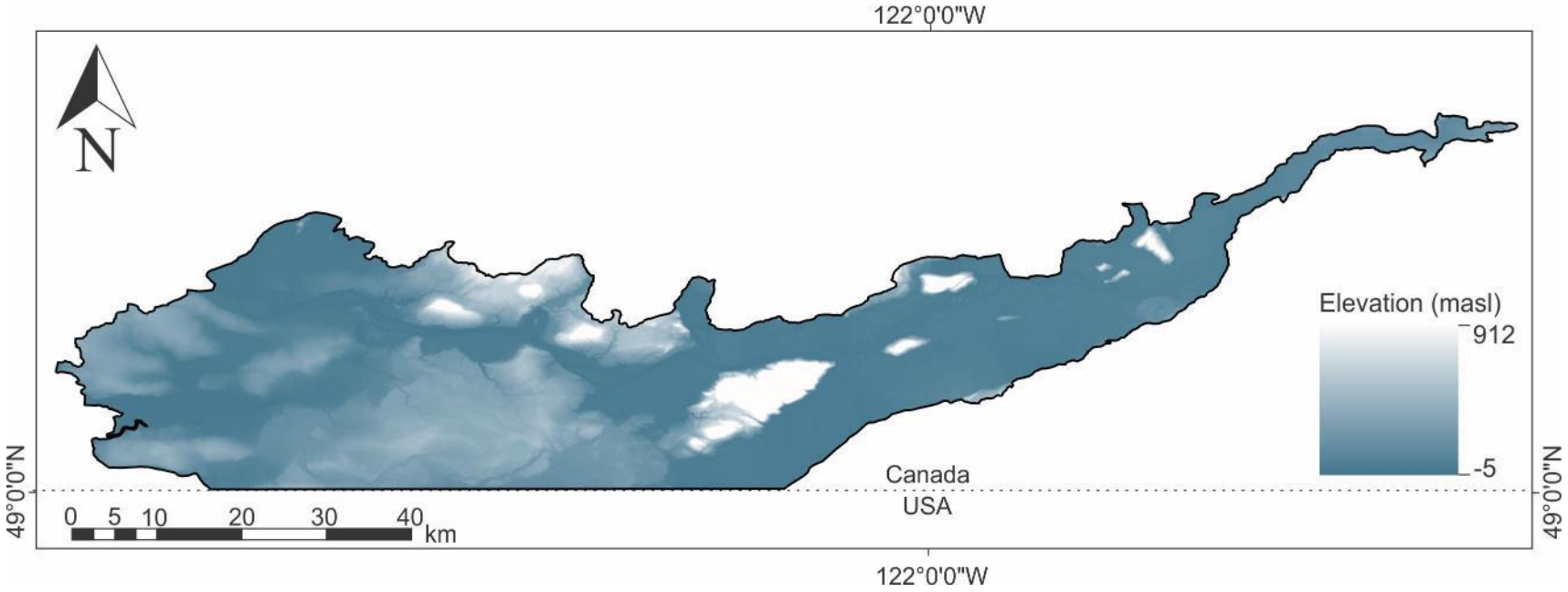

Figure A. 16 Fraser Valley DEM.

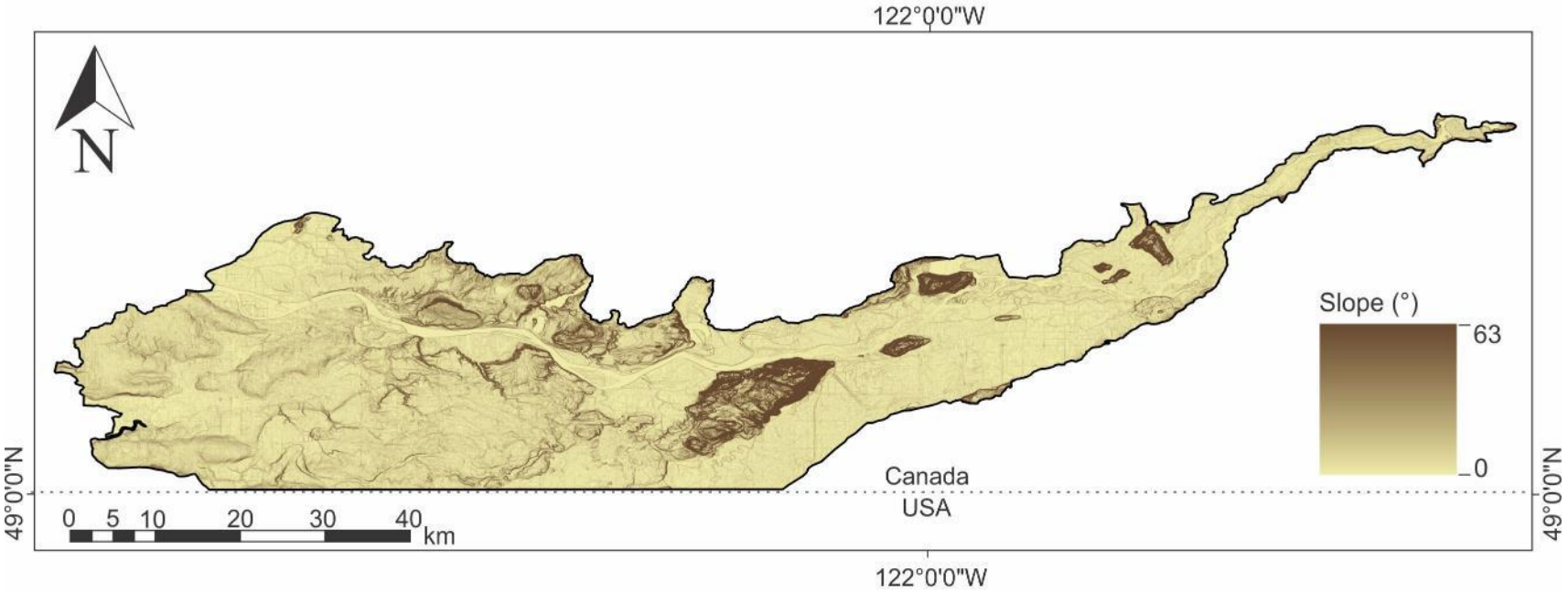

Figure A.17 Fraser Valley slope.

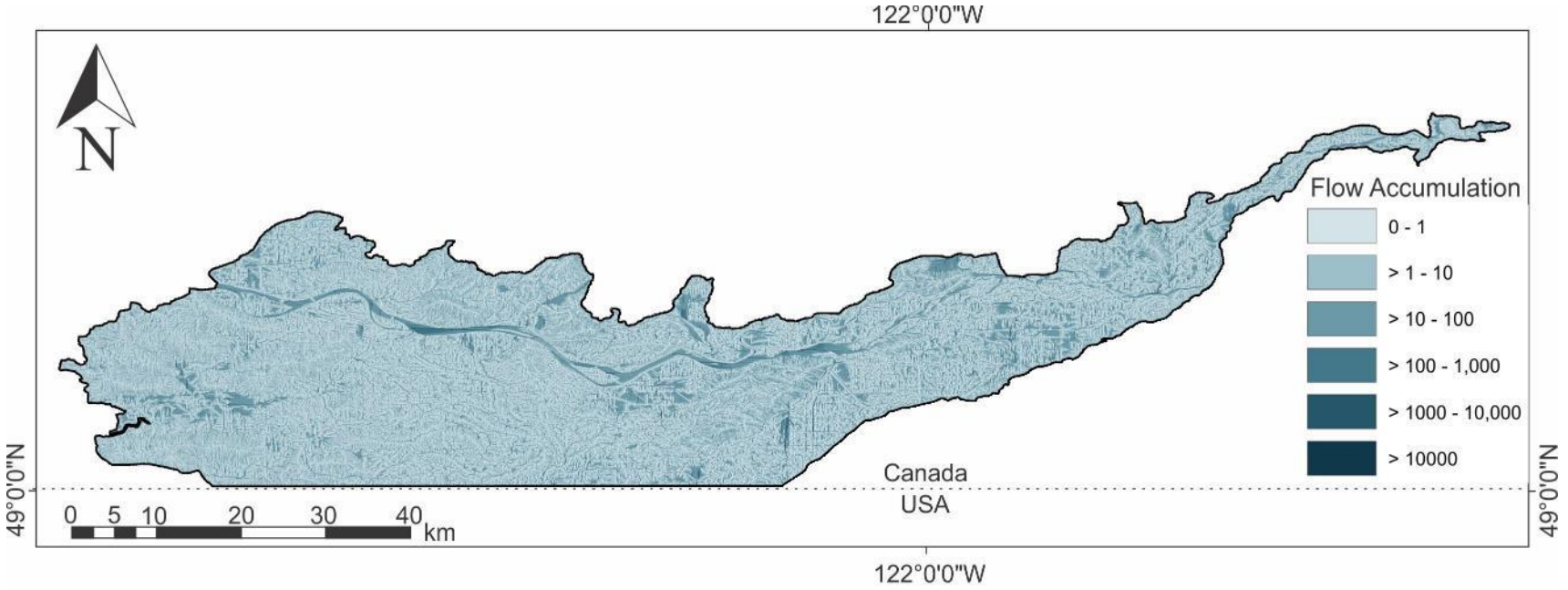

Figure A.18 Fraser Valley flow accumulation.

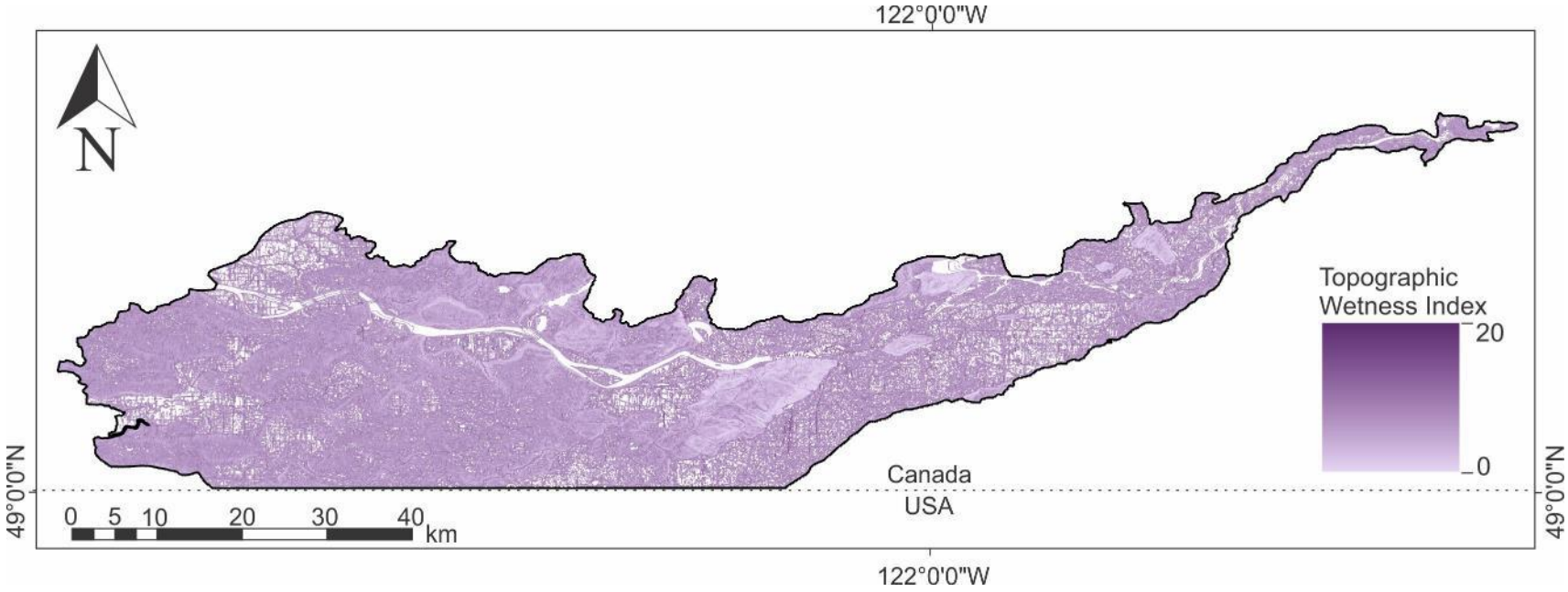

Figure A.19 Fraser Valley topographic wetness index.

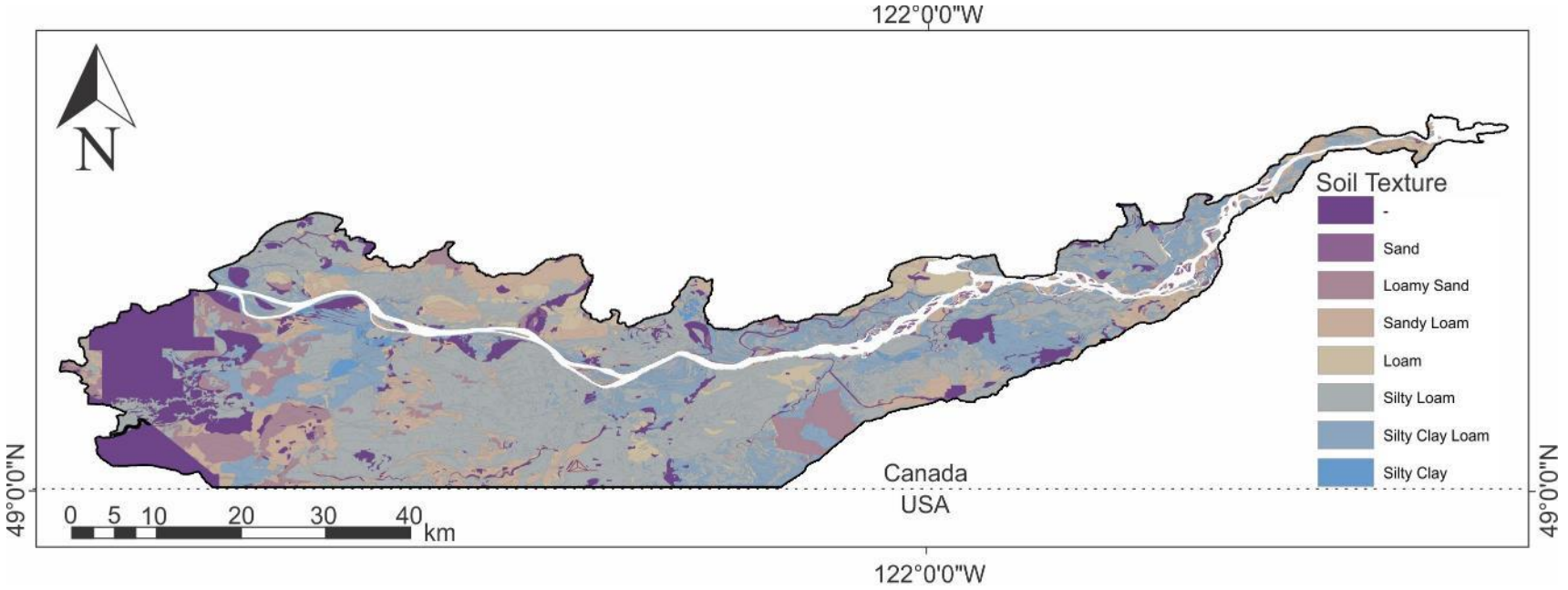

Figure A.20 Fraser Valley soil texture.

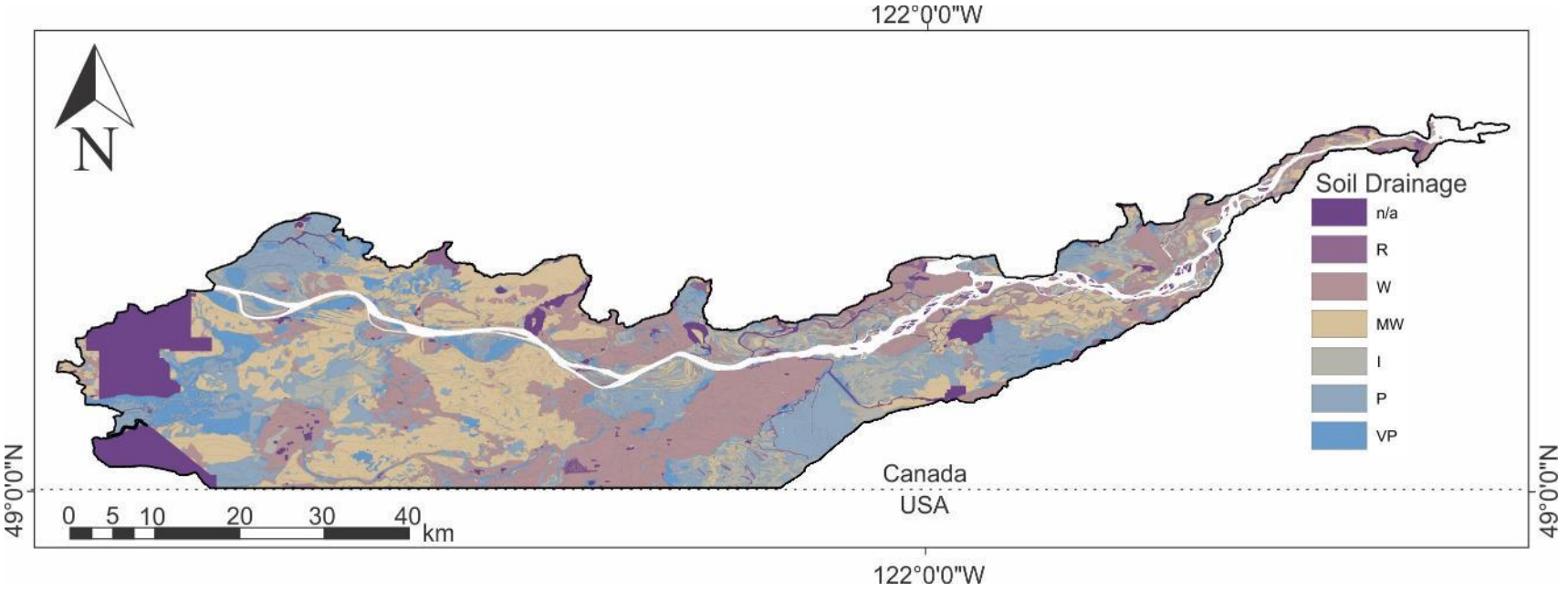

Figure A.21 Fraser Valley soil drainage.

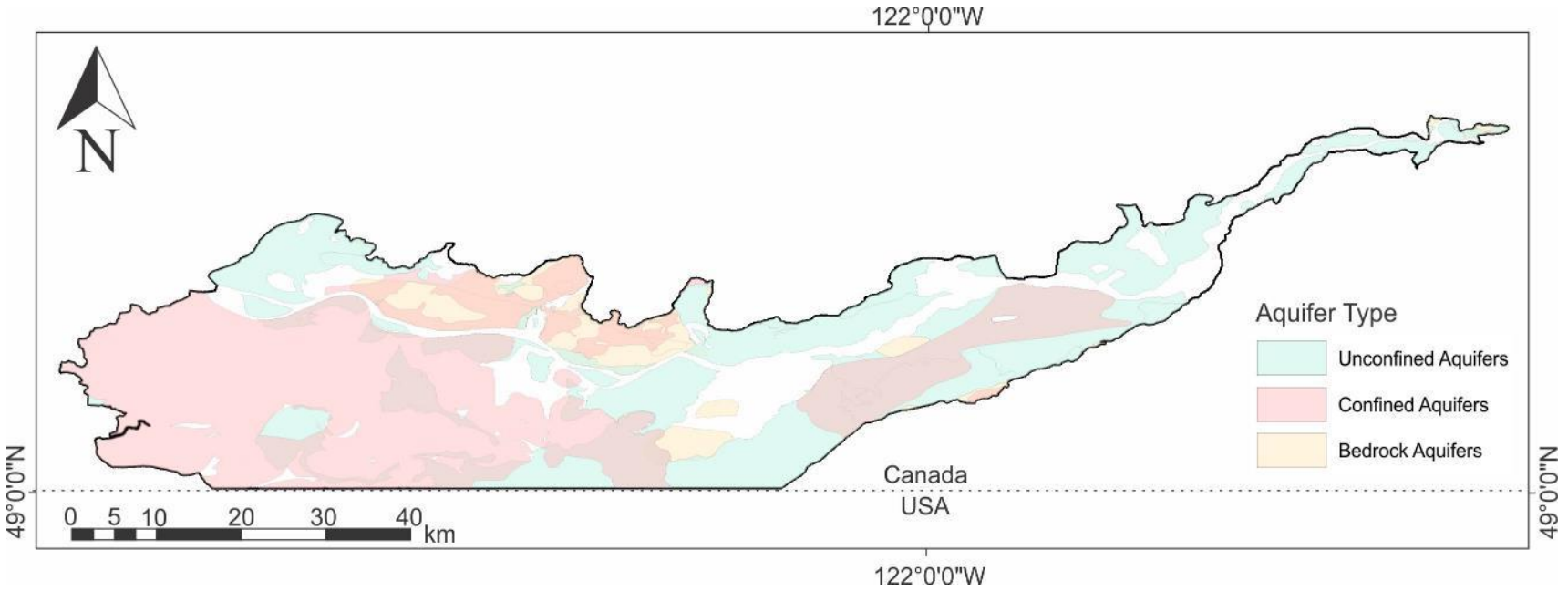

Figure A.22 Fraser Valley aquifers.

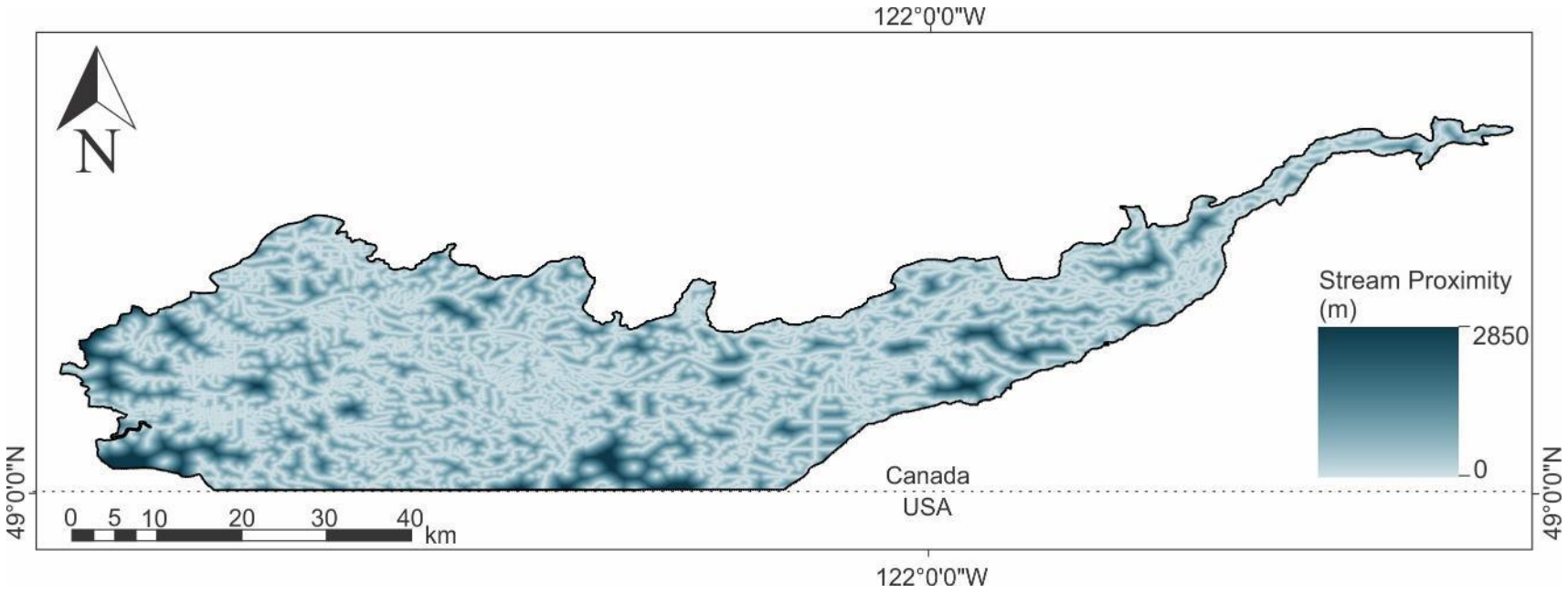

Figure A.23 Fraser Valley stream proximity.

Appendix B: Percent Frequency Graphs

Okanagan Bedrock Context

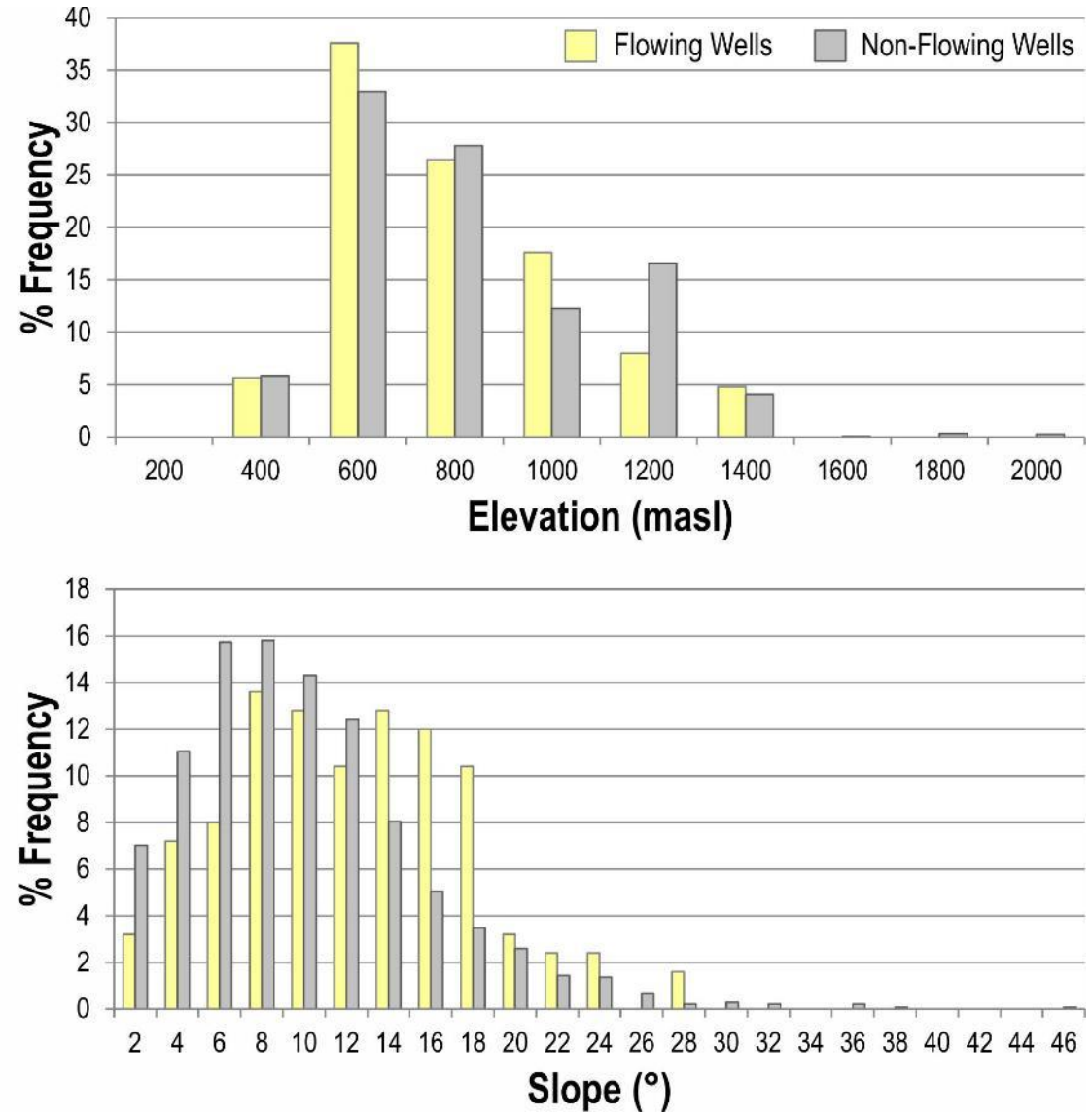

Figure B1 Okanangan Bedrock percent frequency graphs of the occurrence of flowing and non-flowing wells for elevation and slope.

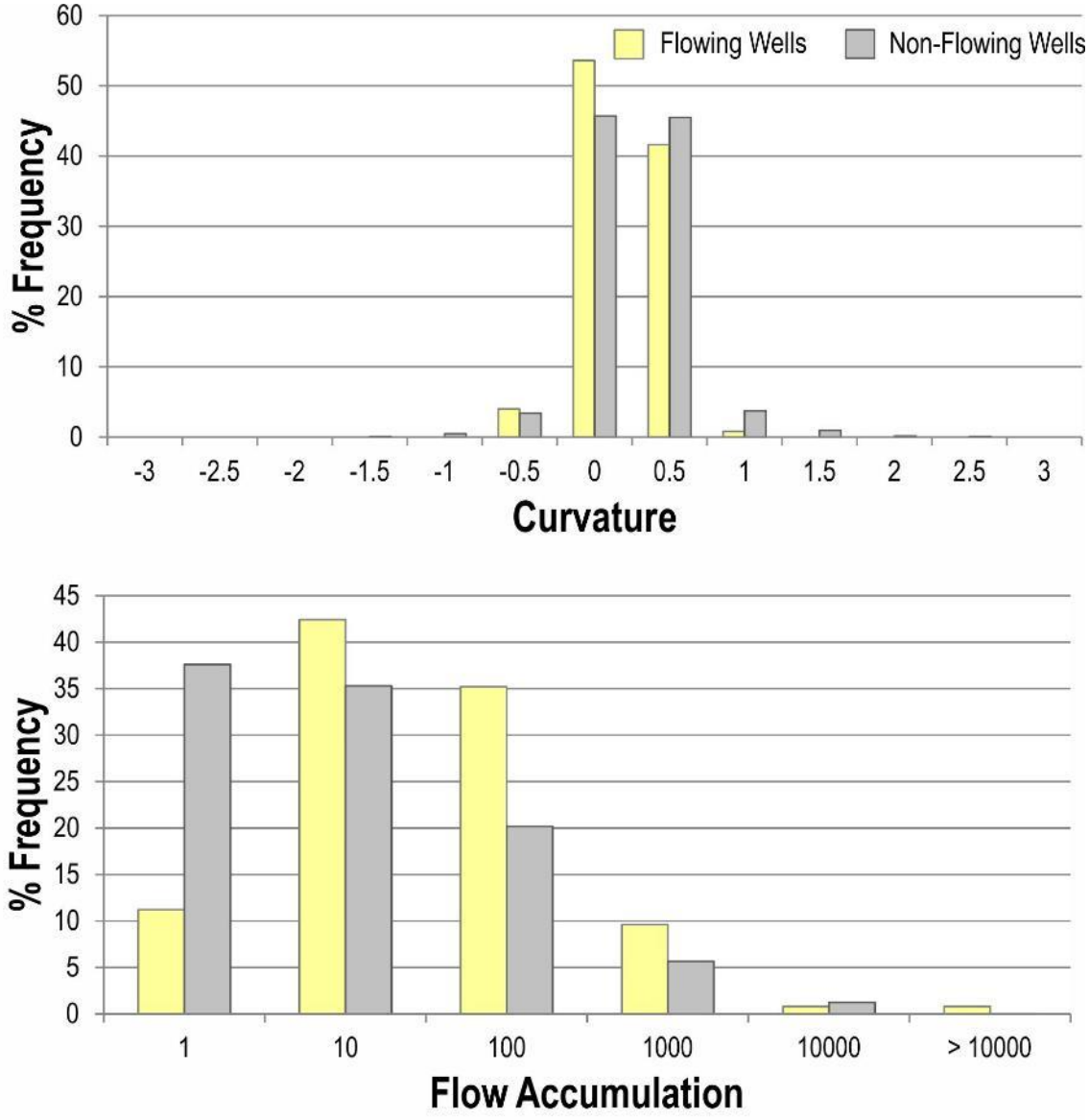

Figure B.2 Okanangan Bedrock percent frequency graphs of the occurrence of flowing and non-flowing wells for curvature and flow accumulation

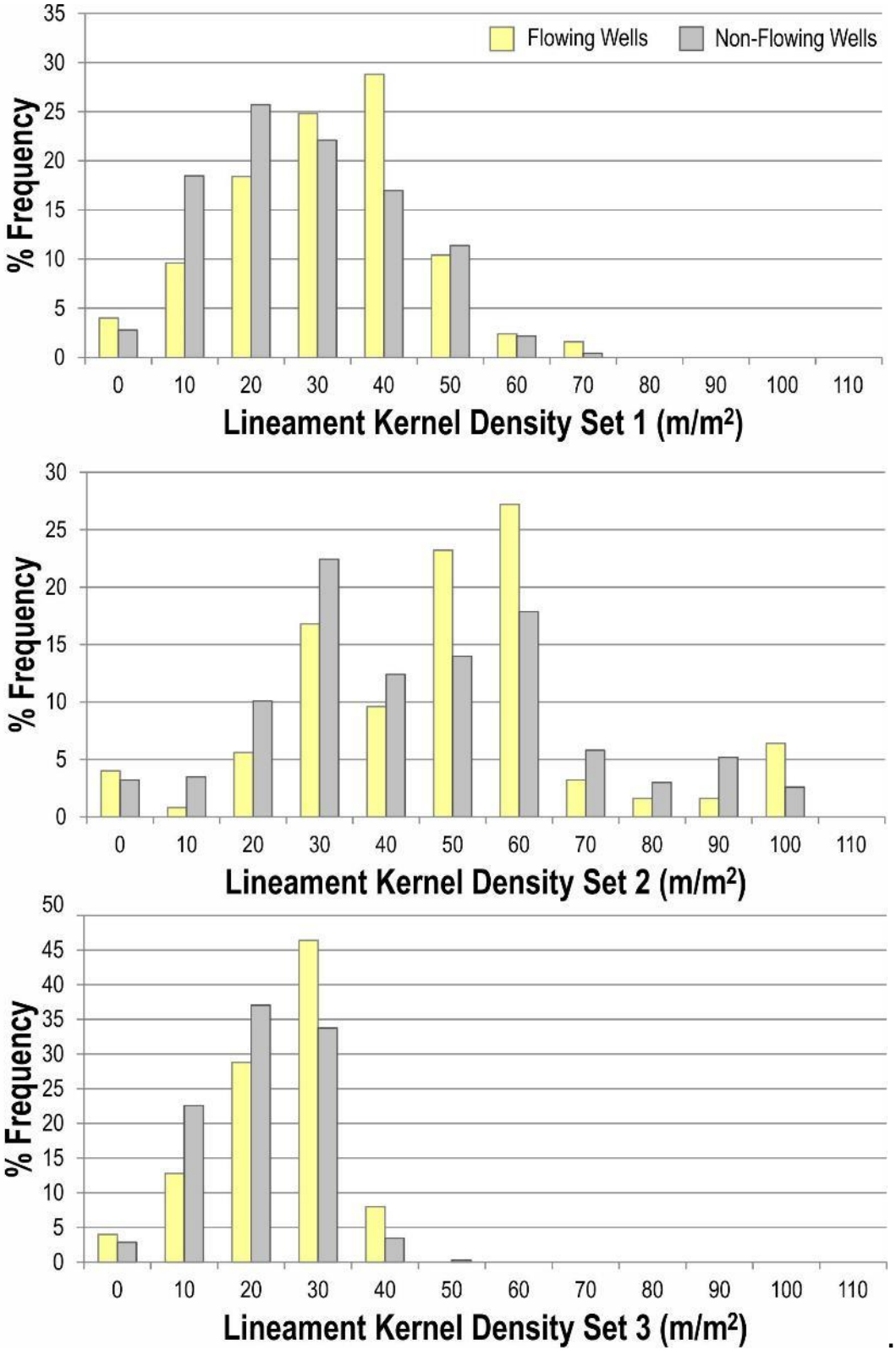

Figure B.3 Okanangan Bedrock percent frequency graphs of the occurrence of flowing and non-flowing wells for the lineament density sets.

Okanagan Unconsolidated Context

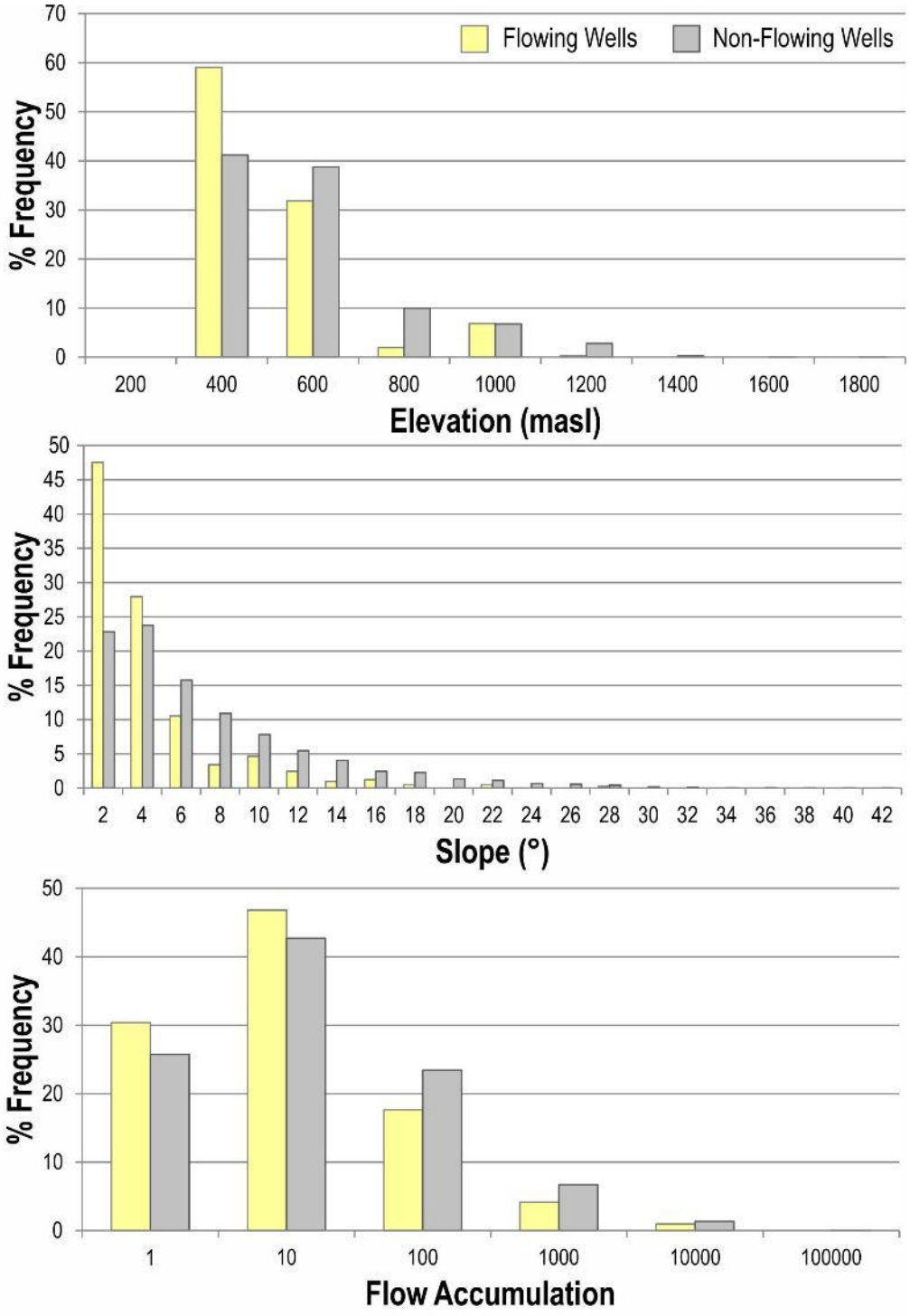

Figure B.4 Okanangan Unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for the elevation, slope and flow accumulation.

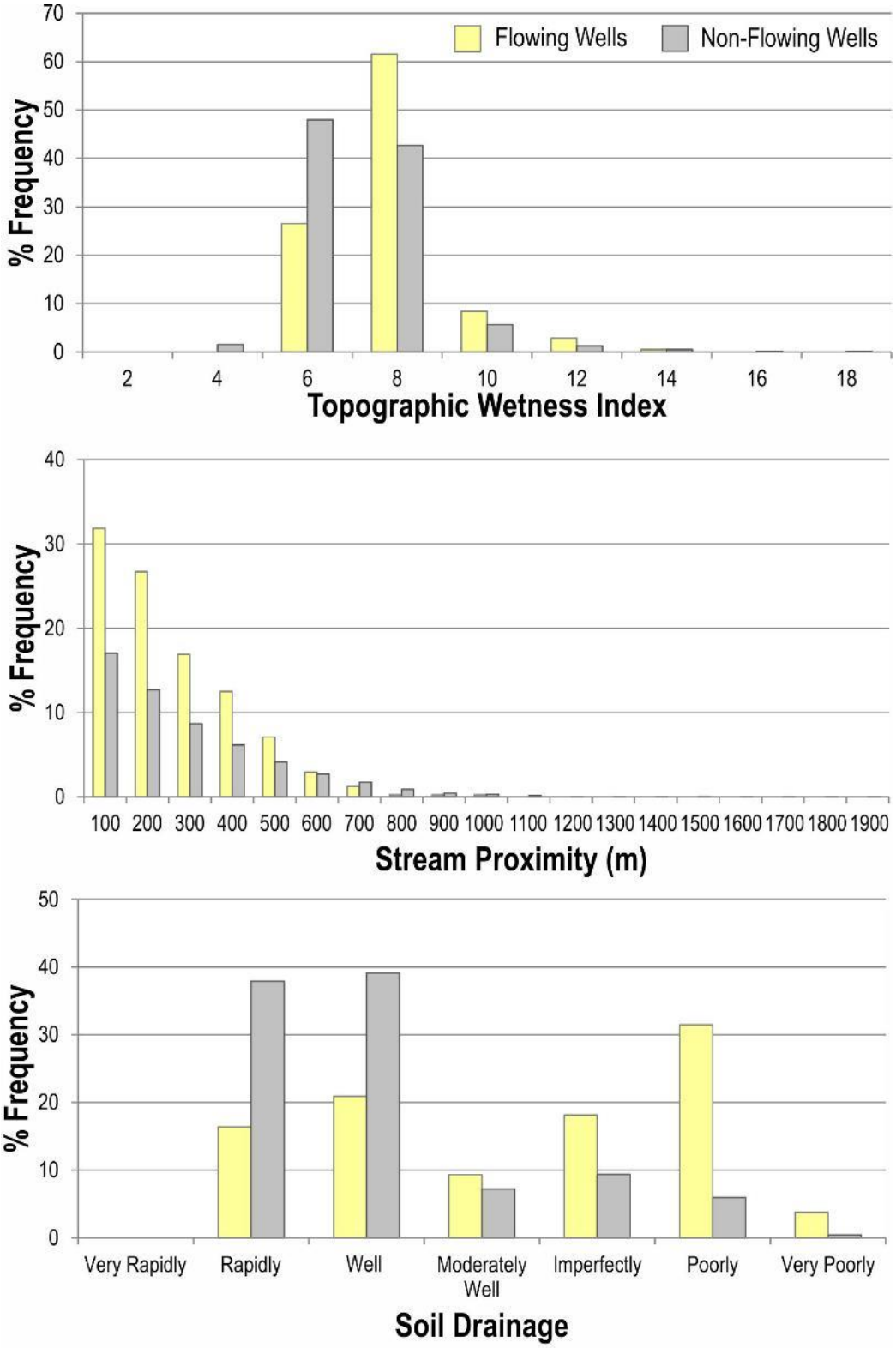

Figure B.5 Okanangan Unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for the topographic wetness index, stream proximity and soil drainage.

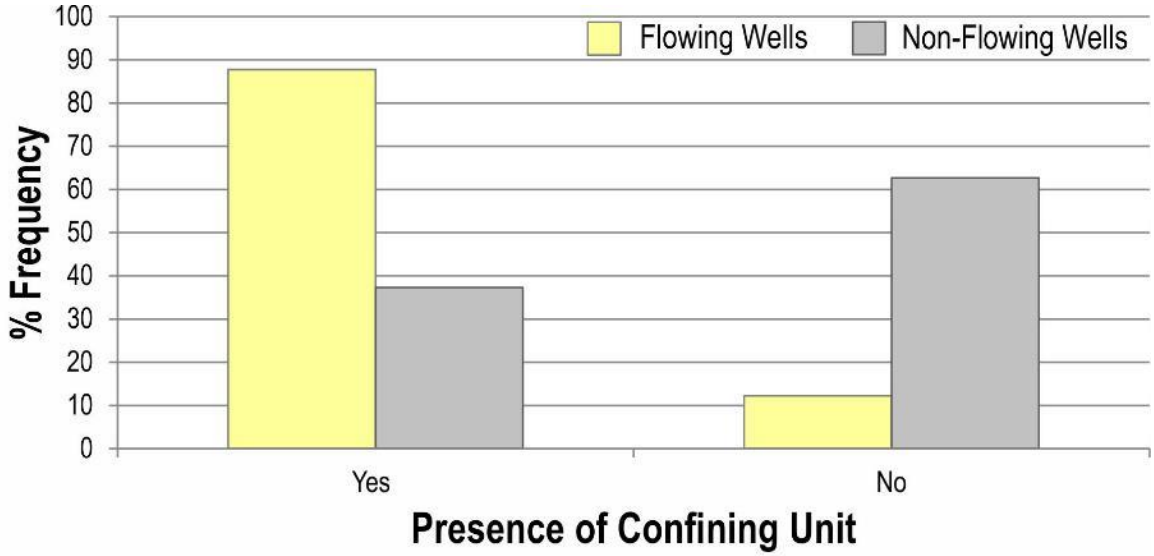

Figure B.6 Okanangan Unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for presence of a confining unit.

Fraser Valley Unconsolidated Context

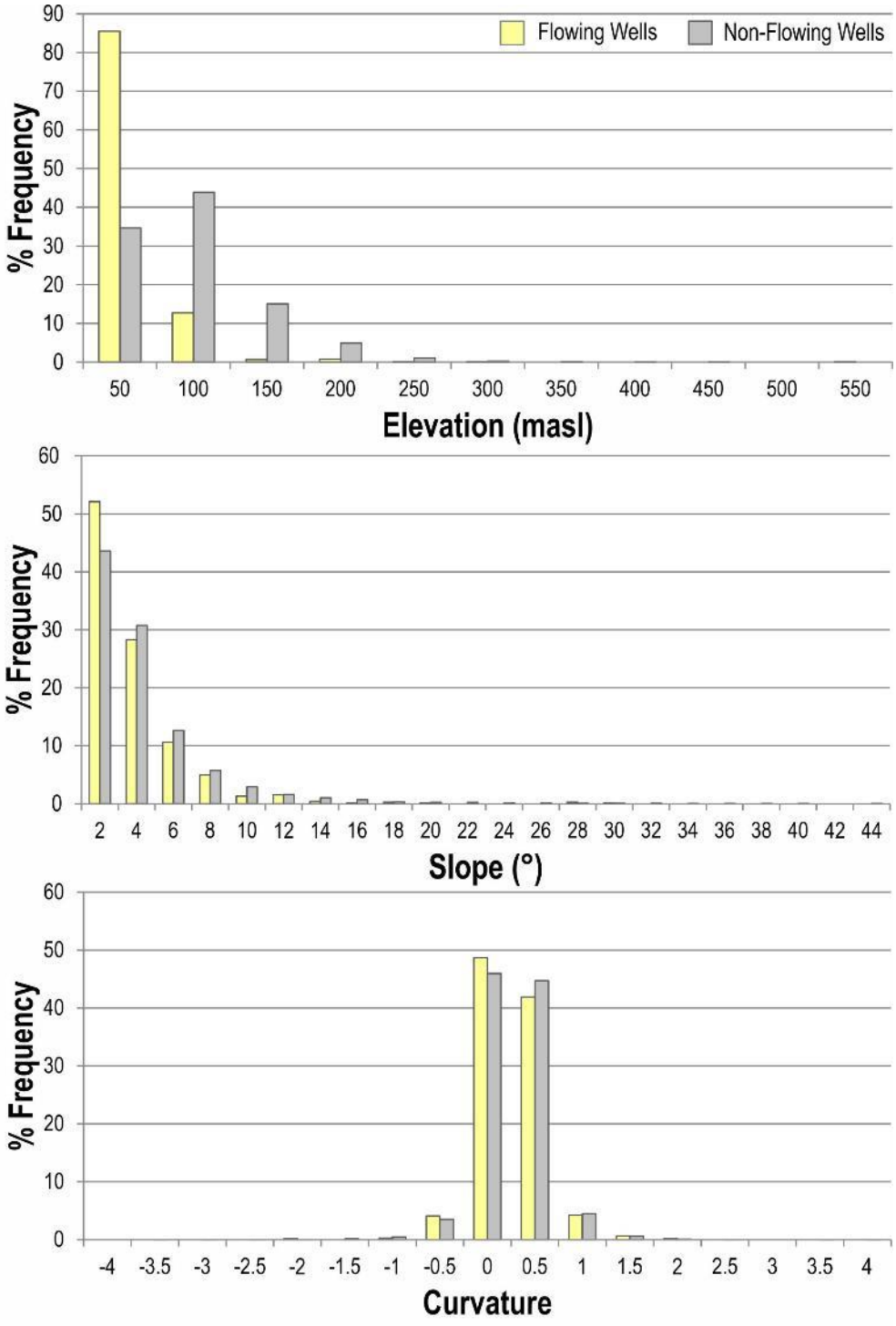

Figure B.6 Fraser Valley Unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for elevation, slope, and curvature.

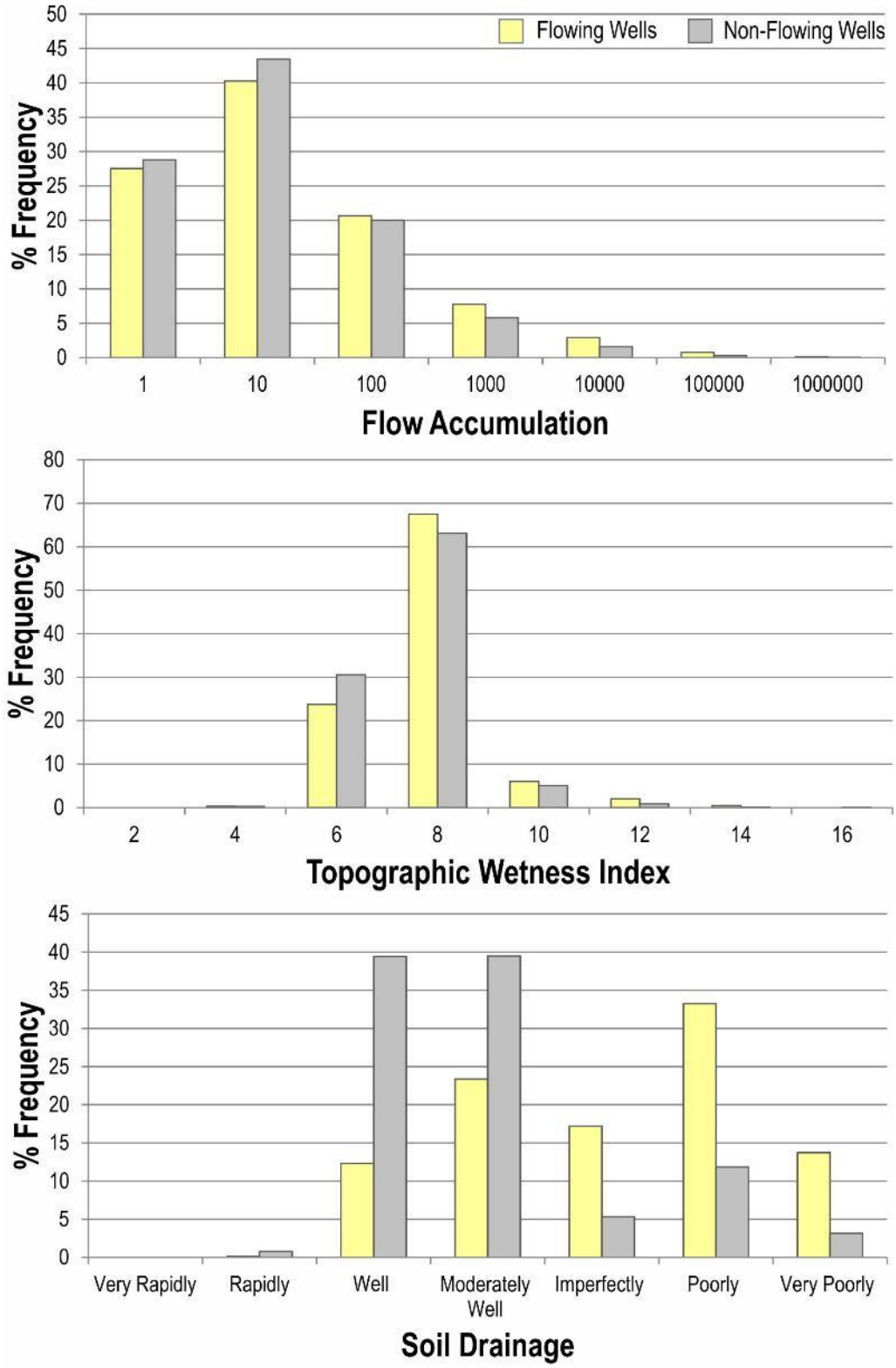

Figure B.7 Fraser Valley Unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for flow accumulation, topographic wetness index, and soil drainage.

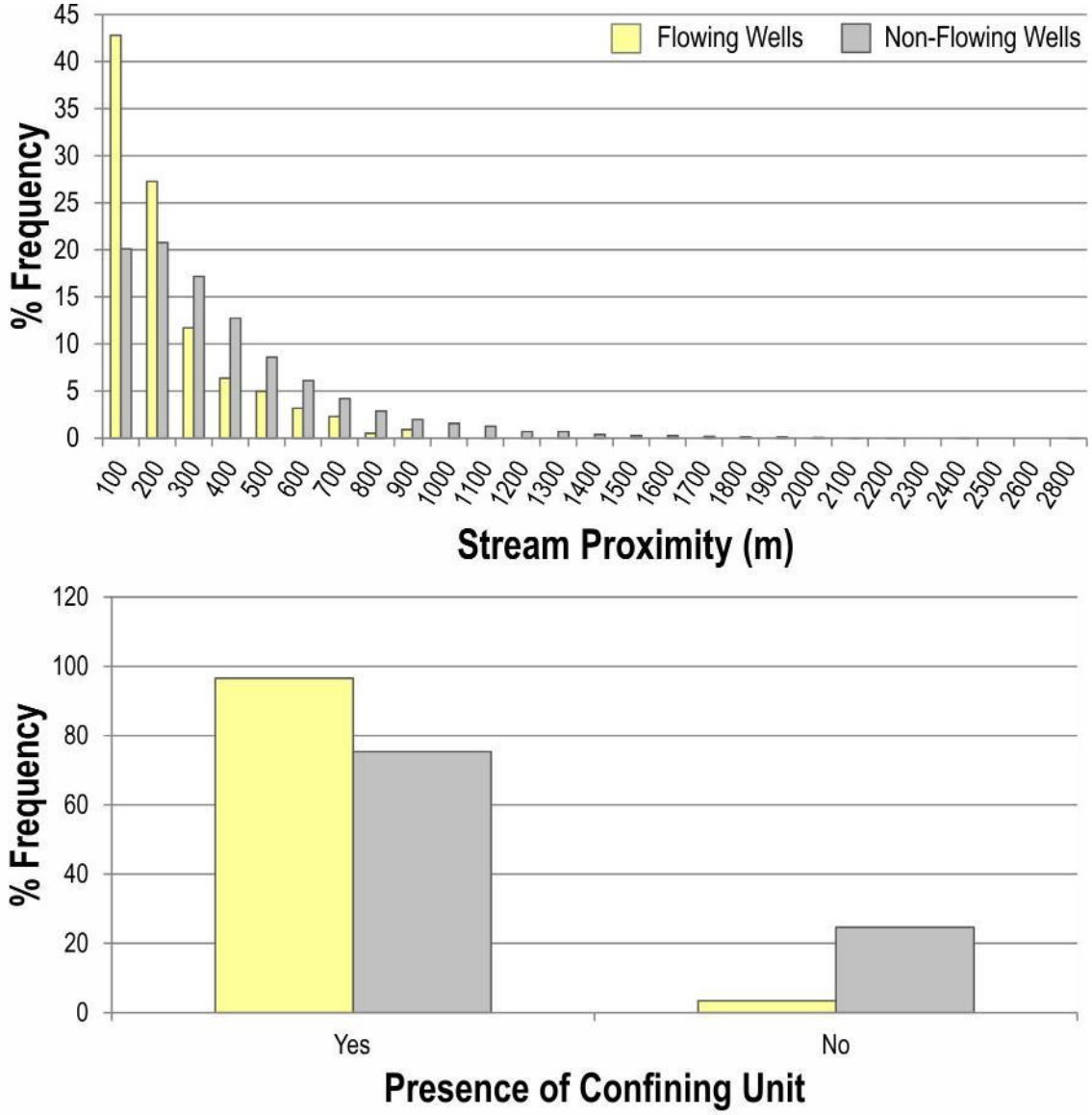

Figure B.8 Fraser Valley Unconsolidated context percent frequency graphs of the occurrence of flowing and non-flowing wells for stream proximity and the presence of a confining unit.

Appendix C.

Supplementary Information for the Analytical Hierarchy Process

Table C.1 Okanagan Bedrock pairwise comparison matrix based on the Wilcoxon Test results and the calculated weights

	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 C.2 Okanagan Unconconsolidated 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 C.3 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

Appendix D Sensitivity Analysis on the bin sizes performed on the Fraser Valley

Overview

A sensitivity analysis was conducted for the Fraser Valley in order to determine appropriate BIN intervals for the 'Factor Standardization' step in the MCA (Section 3.4). The findings from the Fraser Valley were applied to the Okanagan hydrogeologic contexts as well. The 'Examination of Factors' step and the 'Determination of Weights' step were not affected by the BIN intervals and the data processing for these steps were not varied for the sensitivity analysis.

Methods

The sensitivity analysis followed the data processing methodology (Chapter 3) to create three final MCA maps for three different sets of bin intervals. Small, moderate, and large bin intervals were used (Table D.1). 'Small bins' means there are more bin intervals and 'large bins' means there are fewer bins intervals. Each factor had varied bin intervals except for flow accumulation and the presence of confining unit. Flow accumulation values vary over multiple orders of magnitude and because of this the intervals were binned exponentially; therefore, the flow accumulation intervals were not varied. The presence of confining unit factor was also not varied because it is classified simply as present or not present. Each set of bin intervals were standardized according the methods presented in Section 3.4 and the MCA was carried out using Equation 3.21 with the weights from Section 3.5 to create the final MCA maps. The maps were evaluated using the map validation methods from Section 4.4 and evaluated qualitatively to determine which bin interval set was best suited for the MCA.

Table D.1 Bin intervals for the Fraser Valley Unconsolidated sensitivity analysis.

Elevation			Slope			TWI			Flow Acc.	Stream Proximity			Drainage			Confining Unit
Small	Med	Large	Small	Med	Large	Small	Med	Large	All	Small	Med	Large	Small	Med	Large	All
15	50	100	1	2	5	1	2	4	1	50	100	300	R	R, W	R, W, MW,	yes
30	100	200	2	4	10	2	4	8	10	100	200	600	W	MW, I	I, P, VP	no
45	150	300	3	6	15	3	6	12	100	150	300	900	MW	P, VP		
60	200		4	8	20	4	8	16	1000	200	400		I			
75	250		5	10	25	5	10		10000	250	500		P			
90	300		6	12	30	6	12		100000	300	600		VP			
105	350		7	14		7	14		1000000	350	700					
120	400		8	16		8				400	800					
135			9	18		9				450	900					
150			10	20		10				500						
165			11	22		11				550						
180			12	24		12				600						
195			13	26		13				650						
210			14	28		14				700						
225			15							750						
240			16							800						
255			17							850						
270			18							900						
285			19													
300			20													
315			21													
330			22													
345			23													
360			24													

Table D.1 Continued

Elevation			Slope			TWI			Flow Acc.	Stream Proximity			Drainage			Confining Unit
Small	Med	Large	Small	Med	Large	Small	Med	Large	All	Small	Med	Large	Small	Med	Large	All
375			25													
390			26													
			27													
			28													

Results

The MCA maps for the sensitivity analysis are presented in Figure D.1- Figure D.3. The maps are classified via the methods from Section 4.1. Figure D.4 shows the percent frequencies graphs for each sensitivity analysis. Bin intervals where flowing wells occur at higher percent frequencies than non-flowing wells are shown in red. Bin intervals where non-flowing wells are more likely to occur are shown in blue. Generally, larger bin intervals result in more area being classified as 'more likely than not' to have flowing artesian conditions. However it should be noted that the moderate bin intervals (Figure D.2) has a smaller range of 'more likely than not' MCA scores (70 -100 vs. 60 - 100).

The p-values for the Wilcoxon Tests results are displayed in Table D.2. The p-values for each test were examined to determine which bin intervals were best suited for the MCA. Lower p-values indicate stronger evidence that the null hypothesis should be rejected. The moderate bin intervals had the lowest p-values across all tests. When comparing either the analysis wells against the non-flowing wells or all flowing wells against non-flowing wells a lower p-value is desirable as it provides stronger evidence that the hull hypothesis should be rejected. When testing the analysis wells against the validation wells it is desired to have a test result which indicates a 'fail to reject the null hypothesis', therefore making a higher p-value more desirable as the evidence to reject the null hypothesis is less strong. Because the moderate bin intervals had the best results for 2/3 of the Wilcoxon Tests (i.e., both tests in Objective 2) it was selected as the bin interval best suited for the MCA. However, each BIN interval was determined to be valid by the Wilcoxon Test. Indicating that the results for the MCA are not sensitive to the bin intervals.

Table D.2 Wilcoxon Test results and p-values for the Sensitivity Analysis conducted at a 5% significance level.

	Objective 1		Objective 2			
	Analysis vs Validation Wells		Validation vs Non-Flowing Wells		All Flowing vs Non-Flowing Wells	
	p-value	Reject Null Hypothesis?	p-value	Reject Null Hypothesis?	p-value	Reject Null Hypothesis?
Small Bin Intervals	0.76	Fail to Reject	2.32 e -44	Reject	5.66 e- 161	Reject
Moderate Bin Intervals	0.97	Fail to Reject	2.96 e -51	Reject	1.83 e -181	Reject
Large Bin Intervals	0.81	Fail to Reject	6.94 e -36	Reject	1.78 e -130	Reject

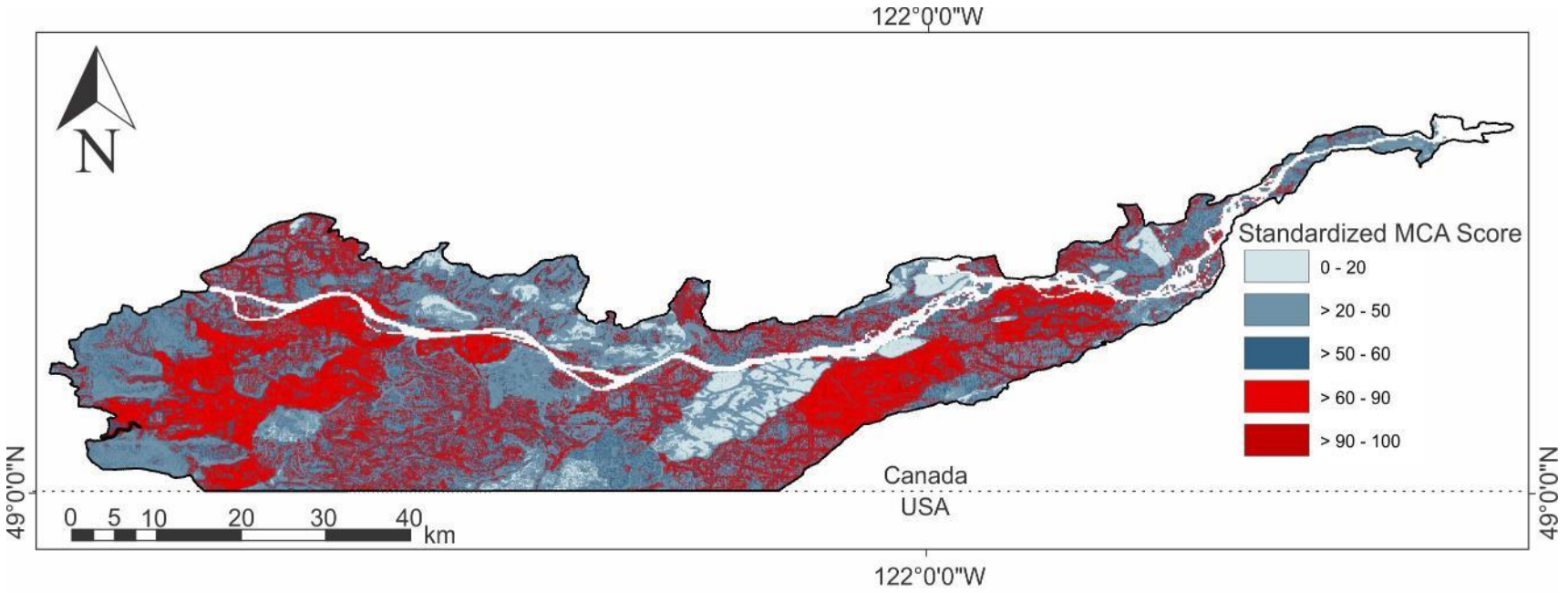

Figure D.1 Fraser Valley Unconsolidated sensitivity analysis MCA map for small binned intervals. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

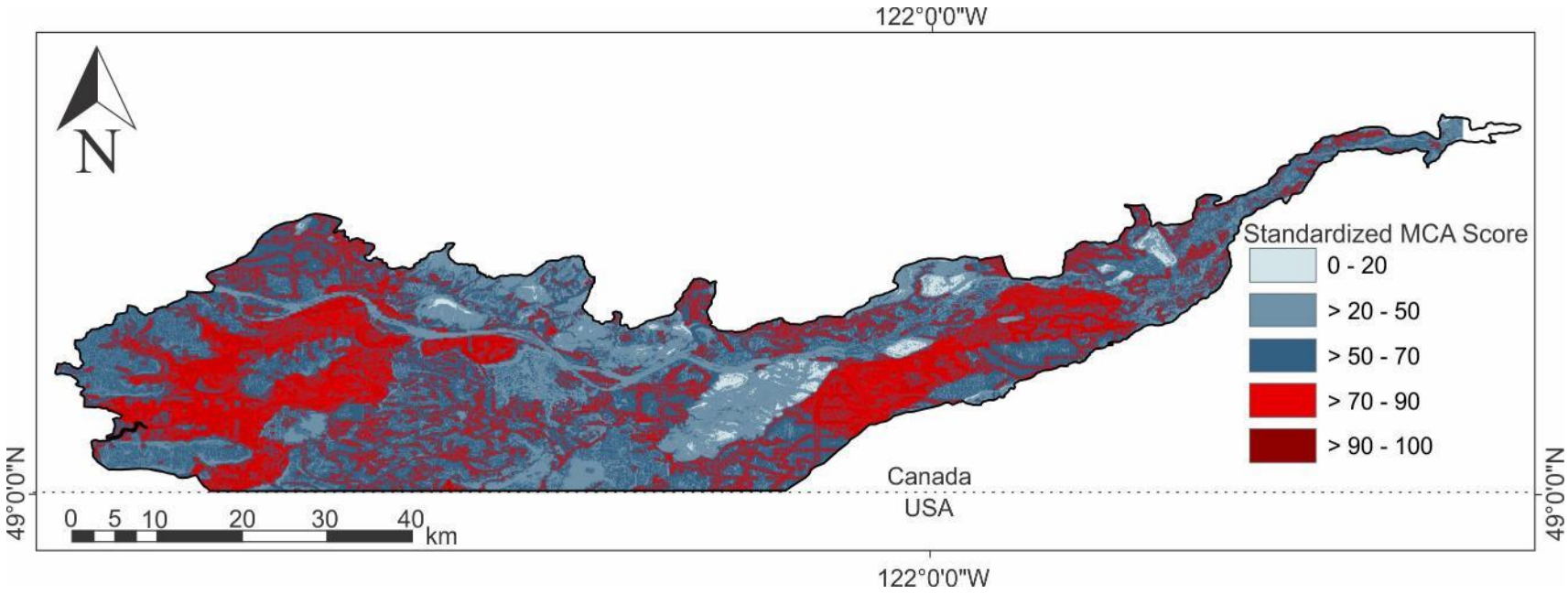

Figure D.2 Fraser Valley Unconsolidated sensitivity analysis MCA map for moderate binned intervals. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

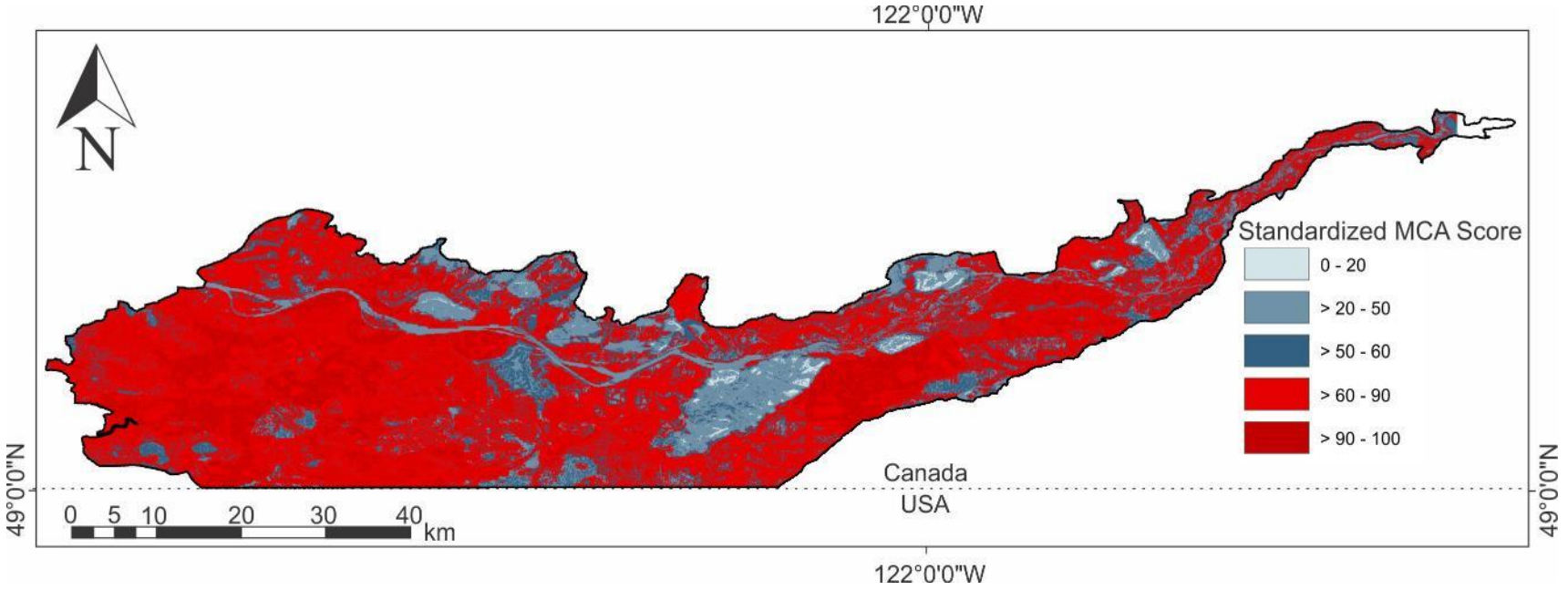

Figure D.3 Fraser Valley Unconsolidated sensitivity analysis MCA map for large binned intervals. Red cells indicate where flowing wells are more likely to occur and blue cells indicate where non-flowing wells are more likely to occur.

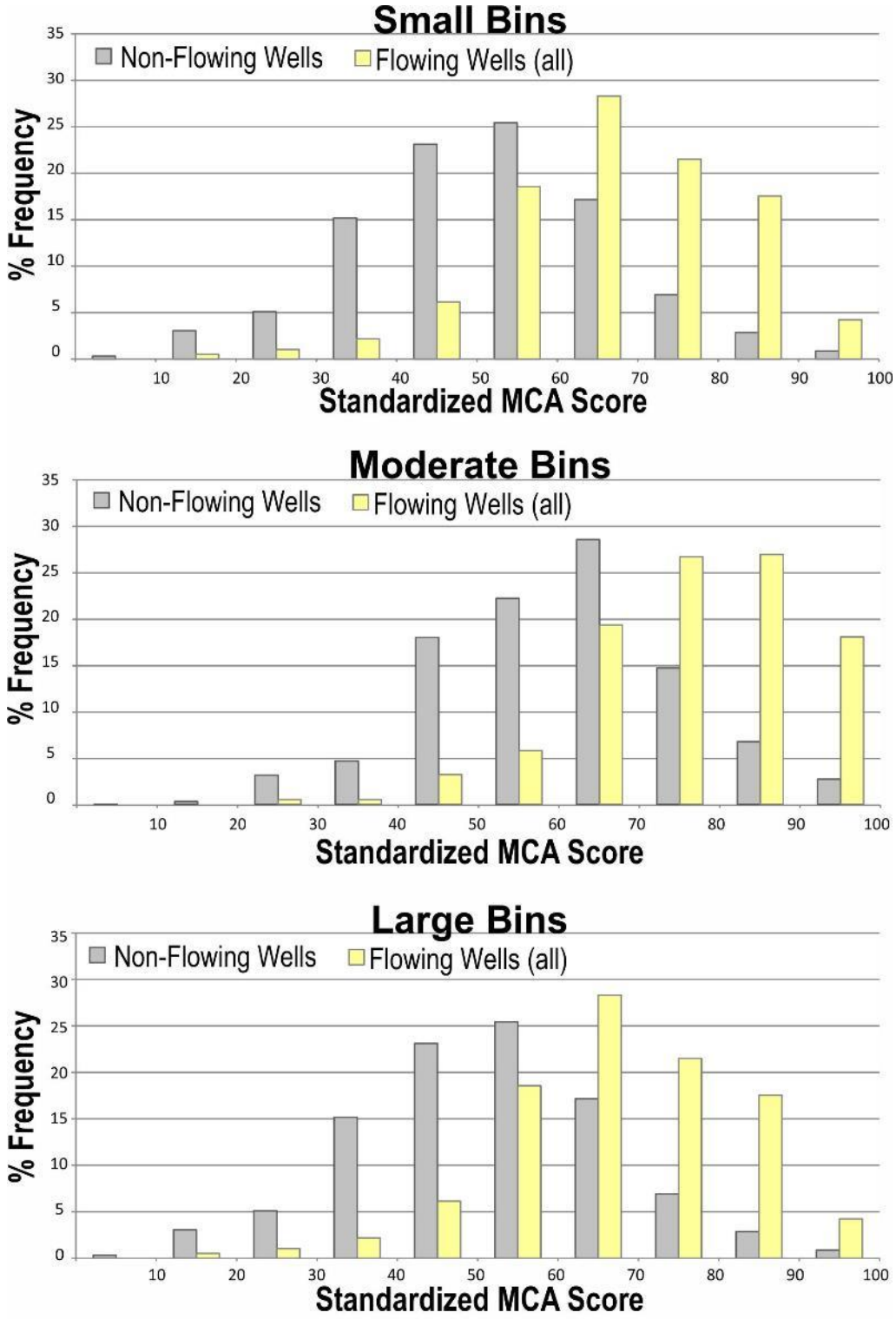

Figure D.4 Percent frequency distributions of all flowing wells (validation and analysis combined) and non-flowing wells for each bin interval in the Fraser Valley sensitivity analysis.