Syilx Okanagan Flood and Debris Flow Risk Assessment

Report 4 of 4 – Quantitative Study (R4) Appendices

R4 List of Appendices

Syilx Okanagan Flood and Debris Flow Risk Assessment

Report 4 of 4 – Quantitative Study

Appendix A: Data Summary

The following provides a list of data used to support the analyses presented in the Quantitative Study.

Legend

Hazard Data
Topographic Data
Exposure Data
Risk Data

Table 1: Summary of data used for Geohazard Risk Assessment

DATA CATEGORY	FILE NAME	DATA DESCRIPTION	Data Purpose	DATA TYPE	SOURCE	CONFIDENCE SCORE
Geomorphic Flood Area (GFA) Model	136_GFA_FloodProne_HighMagnitude.shp 136_GFA_FloodProne_ModerateMagnitude.shp 136_GFA_FloodProne_LowMagnitude.shp	GFA Flood Model	Hazard used as the basis for the flood risk assessment	Shapefile	Ebbwater	3
Debris Flow Hazard Model	136_Palmer_DebrisInitiationandPath	Debris Flow Model. Including the debris flow initiation zones and flow paths	Hazard used as the basis for the debris flow risk assessment	Shapefile	Palmer	4
Geological Soils Mapping	136_GSM Complete.shp	Flood Map Based on Soils Layers. Approach Developed by AE for RDCO	Early Flood Mapping. Flood Map Calibration	Shapefile	Ebbwater	2
Provincial Flood Maps	136_FDRP_floodplains_EPSG4617.shp	Provincial FDRP Flood Maps	Flood mapping calibration	Shapefile	BC Data Catalogue	4
Local Flood Maps	136_Armstrong200yearWSE_EPSG4617.shp 136_MillCreek_200yr_EPSG4617.shp 136_Penticton_Flood_Risk_Assessment.shp	Flood maps produced by previous flood hazard assessments in Armstrong, Mill Creek and Penticton.	Flood mapping calibration	Shapefile	Municipalities	5
GFPLAIN	136_GFPLAIN250.shp	Global geomorphic flood map	Flood mapping calibration	Shapefile	https://github.com/fnardi/GFPLAIN	2

RDCO Flood Assessment	136_RDCO_Flood _AE_Areas.shp	Flood Map Based on Soils Layers. Developed by AE for RDCO	Flood mapping calibration	Shapefile	RDCO	2
Contamination Sources	136_Contamination_sources_combined	Contaminating land uses from BC Assessment Septic Tanks Contamination sources from the BC Environmental Monitoring System	Environment assessment	Shapefile	BC Assessment Authority and compiled property boundaries Interior Health BC Data Catalogue	3
Buildings	136_building_footprints.shp	Polygons of building outlines	Mortality and Affected People assessments	Shapefile	Regional district and municipalities and hand digitized using Bing Satellite Imagery.	4
Census	136_Census_Export_2016_DAs_26910.shp	Polygons of dissemination areas that intersect with study area	Affected People assessment	Shapefile	Statistics Canada via Census Mapper	4
Roads	136_Road_atlas_mainroadsonly.shp	Database of roads in BC	Disruption assessment	Shapefile	BC Data Catalogue	5
Rail	136_rail_track.shp	Database of railway in BC	Disruption assessment	Shapefile	BC Data Catalogue	5
Utility Structures	136_utility_structures	Gas and electric structures	Disruption assessment	Shapefile	EMBC	4
Primary Powerlines	136_ElectricOH_Primary_Transmission	Primary and transmission overhead powerlines	Disruption assessment	Shapefile	EMBC	4

High Biodiversity Areas	136_OCCP_Biodiversity_rank	Ranking of biodiversity hotspots in the Okanagan and Similkameen Watersheds.	Environment assessment	Shapefile	Okanagan Collaborative Conservation Program	3
Drinking Water Wells	136_Drinking_Water_Wells	Location of drinking water wells	Environment assessment	Shapefile	BC Data Catalogue	5
Fish Observations	136_Fish_Observations	BC fish distribution information taken from a combination of all the official provincial databases	Environment assessment	Shapefile	BC Data Catalogue	4
Sylix Archaeology	136_syilx_archaeology.shp	Sylix archaeology and historic sites	Culture assessment	Shapefile	Remote Access to Archaeology (RAAD) via ONA	3
Non-Sylix Archaeology	136_nonsyilx_archaeology.shp	Non-Sylix archaeology and historic sites	Culture assessment	Shapefile	Remote Access to Archaeology (RAAD) via ONA	3
Cultural Buildings	136_cultural_buildings	Buildings with a high social of cultural value from BC Assessment land use data and WFN building footprints	Culture assessment	Shapefile	BC Assessment Authority and compiled property boundaries Westbank First Nation	3

Recreation Trails	136_recretation_trails.shp	Recreation trail including hiking, horse riding, cycling, winter sports, and motor sports	Culture assessment	Shapefile	BC Data Catalogue (road atlas)	5
Land Values	136_Economics_exposure.shp	Total and improved land values	Economy assessment	Shapefile	BC Assessment Authority and compiled property boundaries	
Compiled Property Boundaries	136_Combined_property_boundaries.shp	Combined available parcels layers to fill gaps in individual layers using BC Assessment Fabric, BC Parcels Layer, and WFN Cadastre	Joined with BC Assessment data to create exposure layers for Economy, Environment, and Culture assessments	Shapefile	ICI Society via EMBC BC Data Catalogue Westbank First Nation	3
BC Assessment	136_Commercial Bldg 2019_jurroll.csv 136_Valuation and Land Data 2019_jurroll.csv	Building land use and valuation data obtained for tax purposes	Joined with Compiled Property Boundaries for Economy, Environment, and Culture assessments	Spreadsheet	BC Assessment Authority via ONA	4
Debris Flow - Mortality - Buildings	136_DebrisFlow_Mortality_BuildingFootprints.shp 136_DebrisFlow_Mortality_BuildingFootprints_pnt.shp	Property boundaries in the debris flow hazard area	Mortality Consequence Proxy	Shapefile	Ebbwater	1

Debris Flow - Affected People - Census	136_DebrisFlow_AffectedPeople_Census.shp	Population in the debris flow hazard area	Affected People Consequence Proxy	Shapefile	Ebbwater	3
Debris Flow - Affected People - Buildings	136_DebrisFlow_AffectedPeople_BuildingFootprints_pnt.shp	Properties in the debris flow hazard area	Validation of affected people	Shapefile	Ebbwater	3
Debris Flow - Disruption - Roads	136_DebrisFlow_Disruption_Highway.shp	Highways in the debris flow hazard area	Affected People Consequence Proxy	Shapefile	Ebbwater	3
Debris Flow - Disruption - Rail	136_DebrisFlow_Disruption_Rail.shp	Rail in the debris flow hazard area	Disruption Consequence Proxy	Shapefile	Ebbwater	3
Debris Flow - Disruption - Utility Structures	136_DebrisFlow_Disruption_UtilityStructures.shp	Utility structures in the debris flow hazard area	Disruption Consequence Proxy	Shapefile	Ebbwater	3
Debris Flow - Disruption - Primary Powerlines	136_DebrisFlow_Disruption_Powerlines.shp	Powerlines in the debris flow hazard area	Disruption Consequence Proxy	Shapefile	Ebbwater	3
Debris Flow - Environment - Contamination Sources	136_DebrisFlow_Environment_Contaminants.shp	Contaminants in the debris flow hazard area	Environment Consequence Proxy	Shapefile	Ebbwater	2
Debris Flow - Environment - High Biodiversity Areas	136_DebrisFlow_Environment_Biodiversity.shp	High biodiversity areas affected by contaminants in the debris flow hazard area	Environment Consequence Proxy	Shapefile	Ebbwater	2

Debris Flow - Environment - Drinking Water Wells	136_DebrisFlow_Environment_DrinkingWells.shp	Drinking water wells affected by contaminants in the debris flow hazard area	Environment Consequence Proxy	Shapefile	Ebbwater	2
Debris Flow - Environment - Fish Observations	136_DebrisFlow_Environment_Fish.shp	Fish observations in areas close to contaminants in the debris flow hazard area	Environment Consequence Proxy	Shapefile	Ebbwater	2
Debris Flow - Culture - Sylix Archaeology	136_DebrisFlow_Culture_SylixArch.shp	Sylix archaeology locations in the debris flow hazard area	Culture Consequence Proxy	Shapefile	Ebbwater	2
Debris Flow - Culture - Non-Sylix Archaeology	136_DebrisFlow_Culture_NonSylixArch.shp	Non-Sylix archaeology locations in the debris flow hazard area	Culture Consequence Proxy	Shapefile	Ebbwater	2
Debris Flow - Culture - Cultural Buildings	136_DebrisFlow_Culture_CultureBuilding.shp	Cultural buildings in the debris flow hazard area	Culture Consequence Proxy	Shapefile	Ebbwater	2
Debris Flow - Culture - Recreation Trails	136_DebrisFlow_Culture_Trails.shp	Recreational trails in the debris flow hazard area	Culture Consequence Proxy	Shapefile	Ebbwater	2
Debris Flow - Economy - Land values	136_DebrisFlow_Economic_LandValue.shp	Land values of properties in the debris flow hazard area	Economy Consequence Proxy	Shapefile	Ebbwater	2

Flood - Affected People - Census	136_HighFlood_AffectedPeople_Census.shp 136_ModerateFlood_AffectedPeople_Census.shp 136_LowFlood_AffectedPeople_Census.shp	Population in the flood hazard areas	Affected People Consequence Proxy	Shapefile	Ebbwater	3
Flood - Affected People - Buildings	136_HighFlood_AffectedPeople_BuildingFootprints.shp 136_ModerateFlood_AffectedPeople_BuildingFootprints.shp 136_LowFlood_AffectedPeople_BuildingFootprints.shp	Properties in the flood hazard areas	Validation of affected people	Shapefile	Ebbwater	3
Flood - Disruption - Roads	136_HighFlood_Disruption_Highways.shp 136_ModerateFlood_Disruption_Highways.shp 136_LowFlood_Disruption_Highways.shp	Highways in the flood hazard areas	Affected People Consequence Proxy	Shapefile	Ebbwater	3
Flood - Disruption - Rail	136_HighFlood_Disruption_Rail.shp 136_ModerateFlood_Disruption_Rail.shp 136_LowFlood_Disruption_Rail.shp	Rail in the flood hazard areas	Disruption Consequence Proxy	Shapefile	Ebbwater	3
Flood - Disruption - Utility Structures	136_HighFlood_Disruption_UtilityStructures.shp 136_ModerateFlood_Disruption_UtilityStructures.shp 136_LowFlood_Disruption_UtilityStructures.shp	Utility structures in the flood hazard areas	Disruption Consequence Proxy	Shapefile	Ebbwater	3
Flood - Environment - Contamination Sources	136_HighFlood_Environment_Contaminants.shp 136_ModerateFlood_Environment_Contaminants.shp 136_LowFlood_Environment_Contaminants.shp	Contaminants in the flood hazard areas	Environment Consequence Proxy	Shapefile	Ebbwater	2
Flood - Environment - High Biodiversity Areas	136_HighFlood_Environment_Biodiversity.shp 136_ModerateFlood_Environment_Biodiversity.shp 136_LowFlood_Environment_Biodiversity.shp	High biodiversity areas affected by contaminants in the flood hazard areas	Environment Consequence Proxy	Shapefile	Ebbwater	2

Flood - Environment - Drinking Water Wells	136_HighFlood_Environment_DrinkingWells.shp 136_ModerateFlood_Environment_DrinkingWells.shp 136_LowFlood_Environment_DrinkingWells.shp	Drinking water wells affected by contaminants in the flood hazard areas	Environment Consequence Proxy	Shapefile	Ebbwater	2
Flood - Environment - Fish Observations	136_HighFlood_Environment_Fish.shp 136_ModerateFlood_Environment_Fish.shp 136_LowFlood_Environment_Fish.shp	Fish observations in areas close to contaminants in the flood hazard areas	Environment Consequence Proxy	Shapefile	Ebbwater	2
Flood - Culture - Sylix Archaeology	136_HighFlood_Culture_SylixArch.shp 136_ModerateFlood_Culture_SylixArch.shp 136_LowFlood_Culture_SylixArch.shp	Sylix archaeology locations in the flood hazard areas	Culture Consequence Proxy	Shapefile	Ebbwater	2
Flood - Culture - Non-Sylix Archaeology	136_HighFlood_Culture_NonSylixArch.shp 136_ModerateFlood_Culture_NonSylixArch.shp 136_LowFlood_Culture_NonSylixArch.shp	Non-Sylix archaeology locations in the flood hazard areas	Culture Consequence Proxy	Shapefile	Ebbwater	2
Flood - Culture - Cultural Buildings	136_HighFlood_Culture_CultureBuilding.shp 136_ModerateFlood_Culture_CultureBuilding.shp 136_LowFlood_Culture_CultureBuilding.shp	Cultural buildings in the flood hazard areas	Culture Consequence Proxy	Shapefile	Ebbwater	2
Flood - Culture - Recreation Trails	136_HighFlood_Culture_Trails.shp 136_ModerateFlood_Culture_Trails.shp 136_LowFlood_Culture_Trails.shp	Recreational trails in the flood hazard areas	Culture Consequence Proxy	Shapefile	Ebbwater	2
Flood - Economy - Economics Data	136_HighFlood_Economic_LandValue.shp 136_ModerateFlood_Economic_LandValue.shp 136_LowFlood_Economic_LandValue.shp	Land values of properties in the flood hazard areas	Economy Consequence Proxy	Shapefile	Ebbwater	2

Notes:

1: Data were shared by EMBC (Hayley O'Neil) and restrictions are as follows:

- The data may only be used for the intended purpose and the finished product provided to the ICI Society member upon completion (i.e., the Province)
- Ebbwater may not sell the data, or any part of the data, for any purpose
- Once the project is complete, the data must be deleted from your servers

2: Data were obtained by RDOS (Kelly Chatterson), RDNO (Tom Lenarcic), Vernon (Angie Matheson), RDCO (online) and Kelowna (online). A data sharing agreement was signed with the City of West Kelowna (Mike Bowser).

Syilx Okanagan Flood and Debris Flow Risk Assessment

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Appendix B: Flood Hazard Assessment

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1 Introduction

The Okanagan Nation Alliance (ONA) was a successful Stream 1 applicant to the National Disaster Mitigation Program (NDMP) to study flood and debris flow hazard risk in the Okanagan-Similkameen region. This project is the initial phase of a multi-year flood and debris flow adaptation initiative. This project's goal is to **understand the risk due to flood and debris flows within the project area to support priority-setting of future work**. A key input to this work is flood mapping.

Despite a variety of recent flood-related technical projects that have been recently initiated in the project area (see Appendix D of the Basis of Study for a list of recently completed and ongoing flood-related projects), the flood maps that were available at the time of this assessment were limited. Furthermore, the existing flood maps focus mostly on population centres and do not include rural and uplands areas. To satisfy this project's goal of assessing flood risk over the entire extents of the Okanagan and Similkameen watersheds within Canada, additional flood mapping was required. However, technical flood mapping is resource- and time-intensive. It requires sufficient hydrometric station data as input to hydrologic and hydraulic analysis and modelling to define water levels in streams and flood extents. Such an extensive analysis was out-of-scope for this project.

Throughout this project's progress, an iterative process was used to define areas associated with the natural phenomenon of flood, using progressively more complex and detailed methods. In the early project stages, a preliminary flood assessment was completed. The resulting preliminary flood areas were defined for the following purposes: 1) to review the extent, availability, and usability of existing data, and 2) to produce maps that would be available during the project's engagement activities to obtain qualitative impacts information (see Qualitative Study). For this preliminary mapping, a geology and soil mapping (GSM) method was applied, following a method previously used in the Okanagan watershed (AE, 2016).

In later stages of the project, a more detailed flood assessment was used to delineate flood hazard areas. This more detailed assessment required more time to complete. Using a Digital Elevation Model (DEM), a Geomorphological Flood Area (GFA) tool was applied to define areas for low, moderate, and high flood hazard magnitude scenarios for the project area. The GFA has been shown in several scientific studies to produce good results in characterizing flood prone areas (Manfreda *et al.*, 2011; Samela *et al.*, 2016; Samela, Troy and Manfreda, 2017). Subsequently, the flood prone areas were used as input (along with exposure data) to quantitatively assess consequences, and then risk (see Quantitative Study).

1.1 Project Geographic Scope

The project area includes the Okanagan River watershed including *kłúsx̌nítkw* (Okanagan Lake) and the *nməlqaytkw* (Similkameen River tributary) watershed (Figure 2). The region is a geographic link for many animals, and its climate and landscape support boreal forest species. The *Syilx* people have inhabited the interior plateau since time immemorial, and the project area is located on unceded Territory (see Figure 1 inset). Today, the project area is home to approximately 360,000 people who live in 6 primarily *Syilx* communities (italicized in Figure 1) and over 15 primarily non-*Syilx* communities.

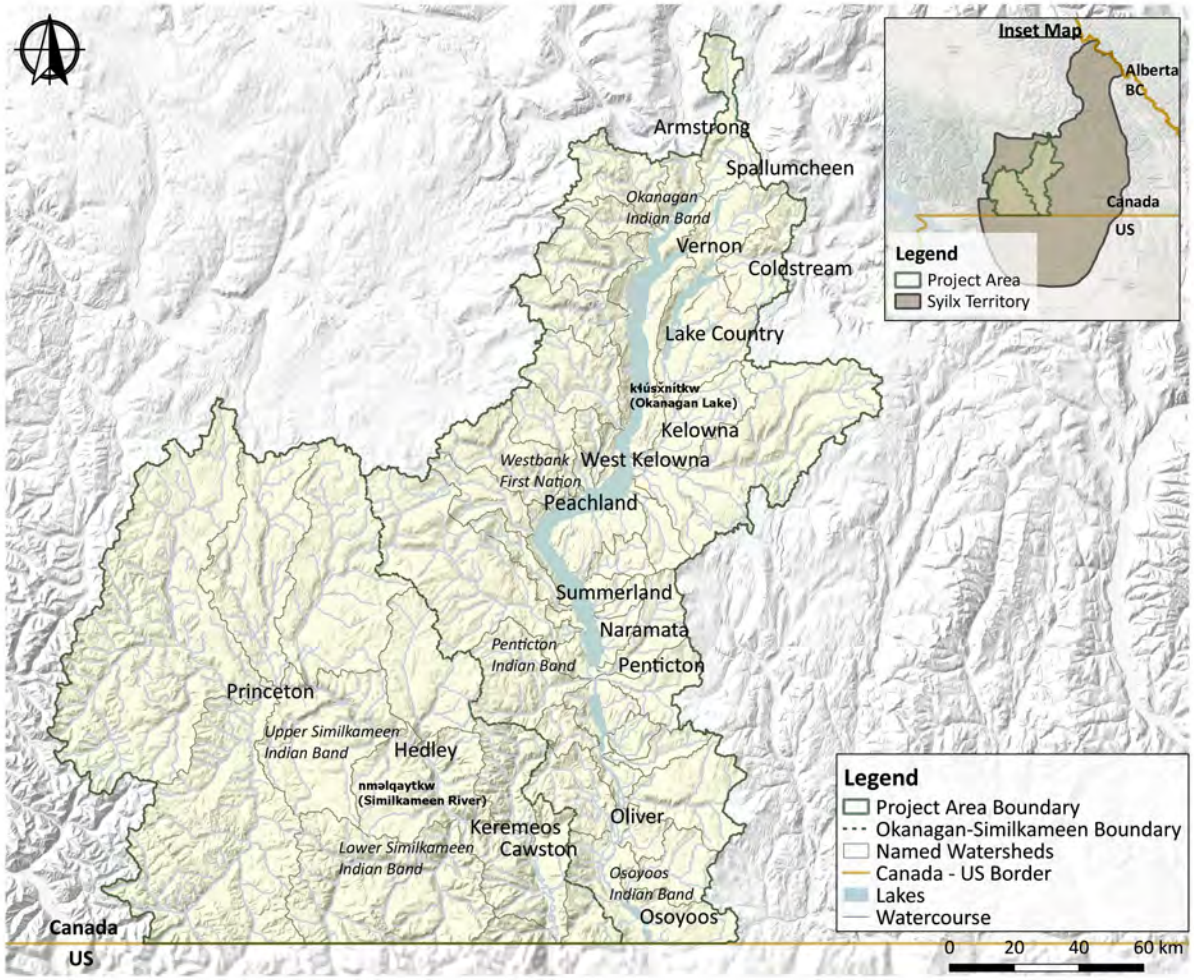

Figure 1: Project Area.

1.2 Objectives of this Assessment

The key objectives of this assessment were to:

1. Review and understand available flood mapping information within the project area.
2. Define preliminary flood hazard areas covering the project area for use in the qualitative impacts mapping during early project engagement activities.
3. Develop a robust method to define higher resolution flood hazard areas of multiple magnitudes for use in the quantitative risk assessment.

2 Review of Existing Flood Mapping Studies

As a first step, existing flood hazard studies were reviewed to determine their coverage and potential strengths and limitations. These existing assessments (shown spatially in Figure 2) also provided calibration and evaluation data for the preliminary and detailed analyses discussed in later sections of this appendix.

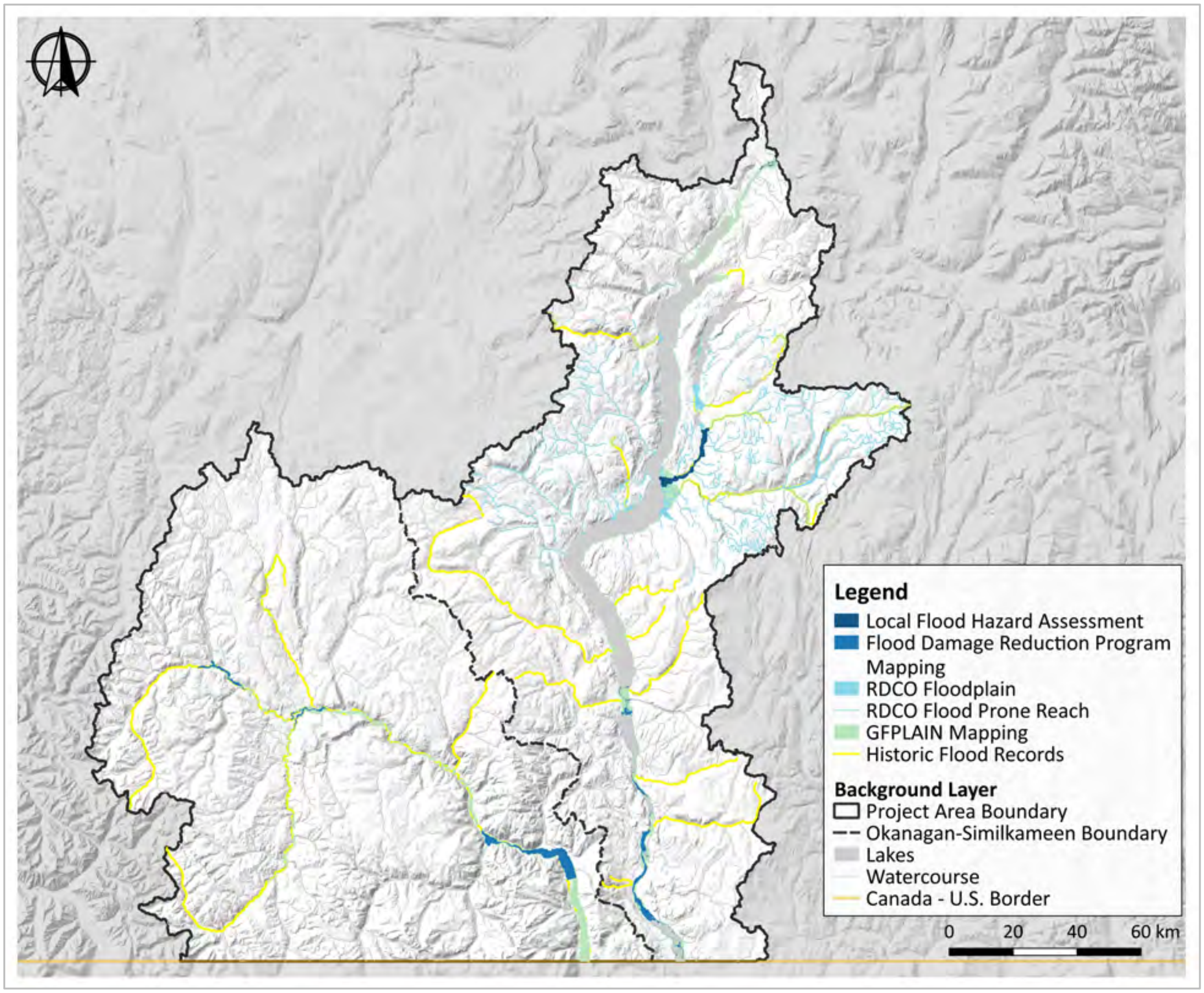

Figure 2: Extents of existing flood hazard mapping, information sources, and analyses in the Okanagan-Similkameen region. Acronyms appearing in the legend are explained in the following sections.

2.1 Hydraulic Modelling-Based Flood Mapping

Flood mapping based on hydraulic modelling output is the most reliable source of flood hazard information available in the project area. These assessments are based on hydrologic analyses and hydraulic modelling of the network of watercourses, and therefore provide more accurate representations of flood extents. However, the geographic coverage of these studies is limited. Summaries of previous mapping studies within the project area, which were reviewed in greater detail, follow below.

2.1.1 Flood Damage Reduction Program

In the 1980s and 1990s the Province of British Columbia (BC) completed a number of flood maps as part of the country-wide Flood Damage Reduction Program (FDRP) with the aim to discourage future development that would be exposed to flooding. FDRP maps for the Okanagan-Similkameen region were developed between 1981 and 1995. They cover Mission Creek, the Tulameen River, the Similkameen River at Princeton and Keremeos, and the Okanagan River from Penticton to Osoyoos (BC Ministry of Environment, 1981, 1984, 1993, 1995b, 1995a). The produced flood extent shows the 0.5% annual exceedance probability (AEP)[1] flood plus a 0.6 m freeboard allowance. The FDRP mapping studies considered neither dikes nor tributary creeks, and focused on the mainstems of the rivers alone. Consistent with model software capabilities of the time, the studies used the HEC2 model software by the United States Army Corps of Engineers (USACE), which simulates stream flows in one dimension (i.e., linearly along stream courses). Then, flood extents were mapped based on modelled flood elevations and topographic land surface contour lines.

2.1.2 City of Kelowna

Flood extents were produced as part of the Mill Creek floodplain bylaw analysis, prepared for the City of Kelowna in 2010 (Associated Engineering Ltd, 2010). This was a detailed flood analysis based on hydraulic modelling using the HEC-RAS-1D software developed by the USACE. This study included a joint probability assessment of the impact of Mission Creek flow and high Okanagan lake levels as well as an assessment of the impact of mountain pine beetle (MPB) infestations. It was concluded that MPB-related impacts to landcover and hydrology led to a flow increase of 24%. The output of this study was a flood map of the 0.5% AEP flood scenario. The flood extent shown in Figure 2 also includes a 0.6 m freeboard allowance.

2.1.3 City of Armstrong

The City of Armstrong completed a flood mapping and risk assessment study in late 2018 (Interior Dams Incorporated, 2018). This assessment reviewed the flood hazard from both Meighan Creek and Deep Creek. A two-dimensional HEC-RAS-2D model (USACE) was developed for the area and calibrated using data collected for the 2018 flood event. Flood maps were produced for the 5% AEP and 0.5% AEP flood scenario.

2.1.4 City of Penticton

The City of Penticton conducted a flood hazard assessment following the flooding in 2017 and 2018 (Tetra Tech Canada Inc., 2018). The assessment identified eleven watercourses in the local area which could influence flood levels in Penticton, including Okanagan and Skaha lakes. The assessment included a wave run-up analysis of the lakes as well as a two-dimensional (2D) hydraulic model of the local watercourses. Flood inundation maps were produced for the 0.5% AEP flood scenario.

Flood maps for different flood magnitudes were produced for a total of 6 dams on Penticton and Ellis creeks. The maps were based on sunny-day and flood-induced dam breach scenarios. Modelled AEPs

[1] The Annual Exceedance Probability (AEP) is the probability of an event of a given magnitude to occur, or to be exceeded, in any given year, typically expressed as a percentage.

ranged from 100% to 0.04%. HydroCAD modelling software was used to determine the flood hydrographs. Climate change was considered by applying an adjustment factor to the AEPs.

2.1.5 Summary of Hydraulic Modelling-Based Flood Mapping

While the above hydraulic modelling studies provide detailed flood maps for specific locations, these maps only cover small sections of the study area with focus on population centres. They can therefore not be used as input for a consistent flood risk assessment throughout the entire study area.

2.2 Geology and Soil Mapping (GSM)-Based Flood study

In 2016, Associated Environmental Ltd. (AE) completed a high-level flood hazard assessment for the whole of the Regional District of Central Okanagan (RDCO), on behalf of the RDCO (AE, 2016). This assessment set out a basic methodology for estimating a worst-case flood extent and identifying flood prone watercourses in order to prioritise future studies over the large study area. The method was based on a combination of geological information, previous flood mapping, and local knowledge. The study consisted of four stages:

1) Identifying alluvial[2] soil material that were likely deposited during a riverine flood, based on Provincial soil databases. The extent of these soils was used to define the extent of historic floods.
2) Mapping flood extents based on previous studies and designated flood construction levels. This included Mill Creek, Mission Creek, as well as Okanagan, Kalamalka, and Wood Lakes.
3) Identifying alluvial watercourses[3] using Provincial datasets. While the flood extent for these watercourses was not calculated, the watercourse lines were mapped as flood prone.
4) Use of a literature review and knowledge from previous projects in the area to refine the above.

While this study provided a consistent approach for the RDCO, it did not cover the entire study area, and was further based on very approximate assumptions of flood prone areas.

2.3 GFPLAIN

The GFPLAIN is a global floodplain study completed in 2019 (Nardi *et al.*, 2019). This assessment used global satellite LiDAR data and a series of open-access GIS-based analysis tools to develop flood hazard areas across the whole globe at a 250 m spatial resolution. The 0.5% AEP flood prone area map for Europe was used to calibrate the model. As the GFPLAIN has not been calibrated locally, the reliability of this global dataset for mapping flood extents in the Okanagan is likely relatively low.

2.4 Historic Flood Event Records

In 2006, a review was completed listing flood and landslide events in BC from 1808 to 2006 for areas in southern BC (Septer, 2006). This report was analysed in recent studies for both the RDCO and the Regional

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[2] Alluvial (or fluvial) material is a general term for all sediment that has been deposited by streams, including gravel, sand, silt, clay and mixtures of these (Brady and Weil, 2008). It is the parent material from which alluvial soils have formed.

[3] Alluvial watercourses are rivers, streams or creeks that flow on alluvial material, in contrast to, for instance, rivers flowing through incised hard bedrock.

District of Okanagan Similkameen (RDOS) for flood events affecting those regions (AE, 2016, 2017). These studies also included updates for more recent years. From these datasets, the approximate location and frequency of historic flooding can be determined. The analysis highlights 4 lakes and 20 watercourses as potentially flood prone in the project area. Mission Creek, Okanagan Lake, Tulameen River and Similkameen River had the most recorded flooding occurrences with 52 separate flood events recorded; more than the other locations combined.

Despite the wide geographic distribution of the data source, it is limited in its applicability due to its lack of spatial consistency. The records are based on reports from people; therefore, they are concentrated in developed areas and do not capture events that occurred where no person was present to observe and record them. Furthermore, the historic flood events mention watercourse names, but the specific locations and extent of flooding along the watercourses are not included.

3 Preliminary Flood Assessment for Qualitative Impacts Mapping

The purpose of the preliminary assessment for qualitative impacts mapping was to provide project participants with a high-level understanding of flood and debris flow hazard areas during early project engagement activities (see Qualitative Study). The more quantitative and detailed method used to define flood hazard areas of multiple magnitudes is described in Section 4.

As described in Section 2, there are a number of previous studies that considered flood hazard within the project area. However, only the GFPLAIN and historic flood record cover the entire project area and both assessments have their limitations. The GFPLAIN was not calibrated to the project area and was done at a relatively low spatial resolution. While this is a useful tool for understanding flood hazard on a global scale, its accuracy is too low for indicating flood hazard at a local scale. The historic flood event record is biased toward developed areas and location descriptions are limited to watercourse names.

Due to the limitations in the existing flood hazard information covering the project area, a preliminary flood hazard assessment was completed for qualitative impact mapping, as described in the following section.

3.1 Expanding the GSM Methodology

Building on the Associated Environmental (AE, 2016) study for the RDCO, the following GSM-based methodology was applied in three stages to define preliminary flood prone areas for the project area:

Stage 1: Identify soil material that was likely deposited during a flood.

Rivers play an important role in erosion of the landscape, and transport eroded materials downstream (Domenico and Schwartz, 1997). Deposition of these sediments can occur for instance at the base of mountains, when steep mountain rivers open into wide flat valleys, flow velocities are reduced, the river 'can carry less' material and therefore deposits suspended sediments. Deposition can also occur during floods, when flood waters extent over natural riverbanks. All sediment material that has been deposited by rivers is called alluvial and includes gravel, sand, silt, clay and mixtures of these (Domenico and Schwartz, 1997; Brady and Weil, 2008). Material can be loose and unconsolidated, or become more consolidated (less loose) over time. Soils that have formed from this material are called alluvial (fluvial) soils. The location of these alluvial soils therefore indicates that at some point, most likely since the last ice age more than 10,000 years ago for soils near the surface but also potentially much longer for deep soil layers, river waters have flown there and deposited sediments.

This is the base assumption when using the existence of alluvial soil as an indicator for previous flooding, as was done in the AE (2016) study, and replicated for this preliminary study.

Provincial soil mapping[4] includes information on the likely method of deposits for soils of each location. This information was used to select all locations that indicated fluvial deposits for the dominant soil type (i.e., the soil type which made up the majority of the soil in the mapped spatial polygon).

Stage 2: Identify alluvial aquifers

The more permeable material of alluvial deposits, such as sand and gravel, within alluvial valleys (i.e., valleys that are characterized by deposition of alluvial sediments) often contains productive aquifers (Domenico and Schwartz, 1997). These aquifers are typically underlain by less permeable deposits such as clay and silt layers, or bedrock. Often, the more permeable deposits that contain aquifers do not extend beyond the floodplain (Domenico and Schwartz, 1997). Thus, the extents of alluvial aquifers can be used as another indicator of flood prone areas.

For this, the Provincial aquifer dataset[5] was used, and aquifers with bedrock (i.e., no sediment deposits) were removed. The remaining aquifer dataset however still includes sediment deposits from other processes (such as glacio-fluvial deposits that were deposited from glacial meltwater during/right after the ice age).

Stage 3: Identify alluvial watercourses

Applying a similar approach as in Stage 1 and 2, but using a different dataset, watercourses that flow on alluvial material were identified, in contrast to, for instance, rivers incised through hard bedrock.

The BC Watershed Atlas[6] provides information on the channel type of river reaches, along with the spatial file. The information indicates whether a river macro-reach has an alluvial or rock-controlled channel type. Alluvial channel types were selected and also mapped as indicators for flood prone systems.

Stage 4: Refine results with existing studies in the area.

Lastly, results from existing flood studies listed in Section 2.1 were used to compare and refine the results from Stages 1 to 3.

3.2 Refinement of Areas

The geological data represented in the GSM analysis are based on a long time scale (hundreds to many thousands of years) throughout which alluvial sediment accumulation have occurred, and during which potentially different climatic and land cover factors have played a different role than today. Therefore, the flood prone area defined from this high-level analysis is considered approximate and preliminary.

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[4] BC Soil Survey by the Ministry of Environment and Climate Change, accessed from https://catalogue.data.gov.bc.ca/dataset/20150a67-5a2d-425f-8216-ff0f97f68df9 in January 2019. Soil surveys were conducted in the 1960-1990s at the provincial and regional scale, and soil attributes in each spatial polygon are based on generalized soil name concepts and are not measured or spatially accurate soils observations.

[5] BC aquifer layer published by the BC Ministry of Environment and Climate Change. Accessed from https://catalogue.data.gov.bc.ca/dataset/099d69c5-1401-484d-9e19-c121ccb7977c in January 2019.

[6] BC Watershed Atlas (channel macro-reaches dataset), published by the BC Ministry of Environment and Climate Change. Accessed from BC Ministry of Environment and Climate Change. Accessed from https://catalogue.data.gov.bc.ca/dataset/099d69c5-1401-484d-9e19-c121ccb7977c in January 2019.

While the likelihood of flood occurrence was not quantified, considering the long time frames over which floods may have deposited sediments, the overall GSM-based preliminary flood extents are likely representative of very low likelihood (very high magnitude) events.

3.2.1 Comparison of Initial Results in RDCO with original AE (2016) study

To refine the method, initial results were compared with the original study completed for the RDCO (Figure 3). While there were large areas of overlap, the reproduced study shows considerably more flood areas around Kelowna (see large patches of blue on east side of Okanagan Lake Figure 3). Consistent with the methodology described in the original study, some aquifer layers were removed based on professional judgment. Removal of some aquifers provided closer match to the original study (Figure 3). The remaining areas of difference were located around Kelowna and Mill Creek. It was assumed that as a specific flood mapping assessment had been completed for Mill Creek, the GSM mapping completed in the original study used the results from that study to replace the GSM approach in the Mill Creek area.

Following the comparison of the results of the reproduction within the RDCO area based on the original study, the GSM method was expanded to the remainder of the project area.

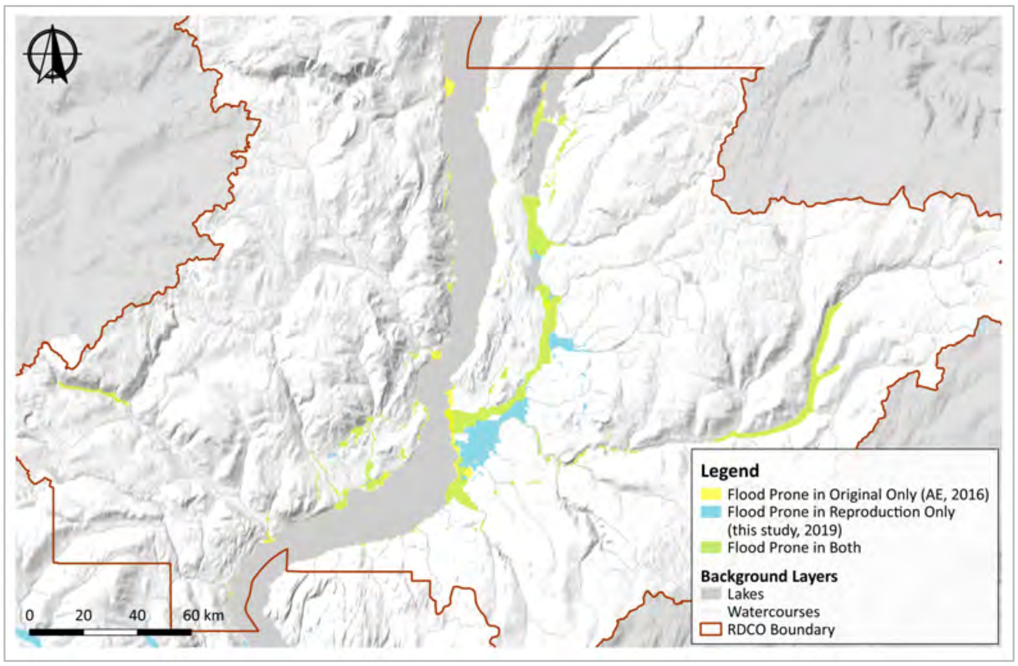

Figure 3: Reproduced flood prone areas compared to the original study.

3.2.2 Evaluation Using FDRP and Recent Hydraulic Flood Maps

To further evaluate the GSM methodology over the project area, the mapping results from Stage 1 to 3 were compared to the FDRP maps at Oliver, Princeton, the Tulameen River and Keremeos, and to flood assessments for Armstrong and Penticton (Figure 4). While the GSM flood extents are generally larger than those sourced from the FDRP maps, the proportion of overlapping areas is high. The discrepancy in areas that do not overlap may be caused by the fact that the GSM layer includes tributaries that are missing from the FDRP modelling and resulting maps. Another difference is that the FDRP and detailed assessment maps represent a moderate flood hazard magnitude of 0.5% AEP plus freeboard, whereas the areas developed using the GSM method are likely representative of an unquantified magnitude event that can be characterized as approximately “very high”.

The GSM and FDRP flood extents compared less well for the Armstrong and Penticton areas. The river network at Penticton is highly managed through an extensive series of dikes. As soils would have been deposited before the dikes were constructed, the GSM-derived flood prone area is much larger than indicated in recent flood maps that incorporated the channelized character. The GSM flood prone areas for this area, however, can approximate a high-level illustration of the potential flood prone areas under dike failure conditions. Similarly, flooding in Armstrong is highly controlled by the railway embankment at the northeastern edge of the town and the effect that canalisation of Deep Creek has through the city. This means that the river is not following its historic path as indicated by the GSM layer. It should also be noted that the Armstrong study area was limited to the City only; therefore, it does not include the large areas shown as flood prone in the GSM to the east. Professional judgment was used to determine where FDRP maps should be included within the preliminary flood area maps as input for the qualitative risk mapping.

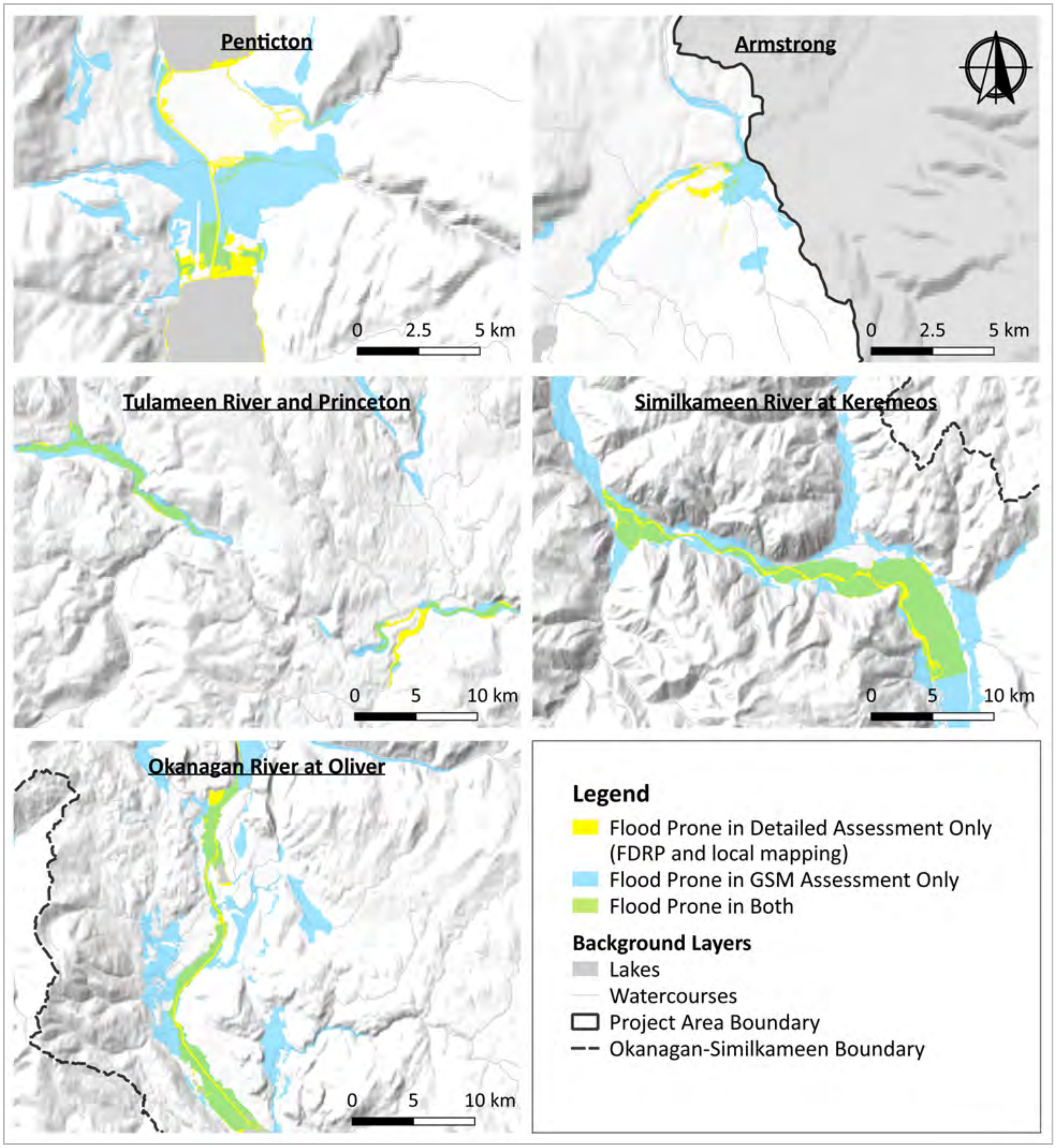

Figure 4: Comparison of GSM outlines with previous flood hazard assessments.

Despite the discrepancies in flood mapping areas shown in the examples above, the method used was valid for the purpose of developing preliminary flood prone area maps for engagement. A more robust flood analysis was completed for the quantitative assessment (Section 4).

3.2.3 Preliminary Flood Prone Area Map

The preliminary GSM-based flood prone area map is presented in Figure 5. The map reflects differences in flood areas based on geological and terrain factors affecting watercourses and waterbodies. For example, the southern portions of the Similkameen watershed have a dense network of alluvial watercourses; this is likely reflective of the steep terrain creating dynamic conditions in these areas of the watershed.

The purpose of the preliminary mapping exercise was to provide project participants with a high-level understanding of potentially flooded areas. For the engagement activities, the preliminary debris flow hazard areas (see Appendix C of the Quantitative Study) were added to the preliminary flood prone areas (see maps shown in the Qualitative Study).

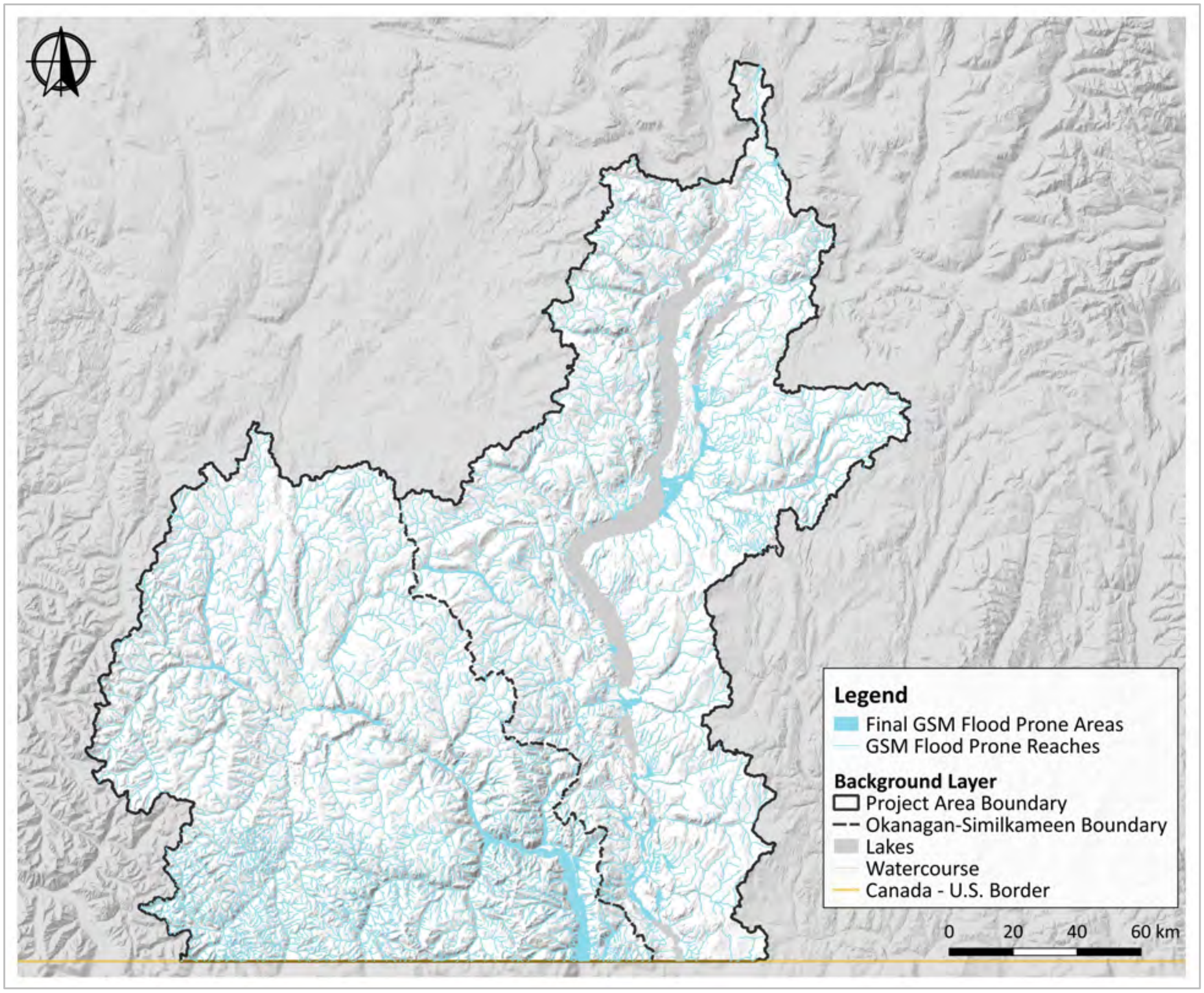

Figure 5: Finalized preliminary flood areas map used for engagement activities.

4 Quantitative Flood Assessment for Quantitative Consequence Mapping

The quantitative flood assessment followed the engagement activities (and the preliminary flood assessment used to support those activities), as more time was required to complete it. The purpose of this more detailed flood hazard assessment was to generate flood prone areas of different flood magnitudes, which can be used in a quantitative risk assessment. These flood scenarios were used as the basis to calculate risk scores and risk matrices as described in the Quantitative Study. For this more detailed flood hazard assessment, the Geomorphic Flood Area (GFA) tool was applied across the project area.

4.1 Understanding the GFA Methodology

The geomorphology of a landscape is shaped by many factors (e.g., climate drivers, water flows, geology, sediment transport, landcover, and land use (Samela, Troy and Manfreda, 2017)). Over a long time (many thousands of years), hydrological extremes can shape geomorphological features through erosion, sediment transport, and deposition (Samela, Troy and Manfreda, 2017). This is the underlying assumption for using geomorphological (landscape) features in determining potentially flood prone areas.

In hydrology, many methods have been developed that relate topographic descriptors (topographic indices) to potential floodplain extent (Samela, Troy and Manfreda, 2017; Samela *et al.*, 2018). The basis for these analyses is typically a digital elevation model (DEM), from which geomorphological landscape characteristics can be deduced. The GFA tool applies such a geomorphic approach, and is available as a software package add-on to the open-source GIS software QGIS (Albano *et al.*, 2018) that allows users to conduct the above DEM analyses.

However, it is important to highlight that a geomorphological analysis does not account for rainfall-runoff processes[7] and interaction with infrastructure (such as flood defences). Thus, the tool can only identify potentially flood prone areas.

4.1.1 Equations

The GFA tool defines locations within a river basin as either flood prone or not flood prone. The classification is based on the Geomorphic Flood Index (GFI), which is calculated using landscape characteristics of the river basin (Samela, Troy and Manfreda, 2017; Samela *et al.*, 2018) as follows:

$$GFI = ln\left(\frac{h_r}{H}\right) \qquad \text{Equation 1}$$

where for each location in a basin (for example for the location under exam in Figure 6), the GFI compares the water level h_r [m] in the river with the elevation difference H [m] between the two points (Figure 6).

[7] Rainfall-runoff processes typically refer to the movement of precipitation (rain or snow) through a watershed. They include surface runoff, infiltration, interflow through the soil layer, percolation to an underlying aquifer, baseflow to rivers, transpiration through vegetation and evaporation from exposed soil. Rainfall-runoff processes will vary strongly depending on topography (e.g., steepness of slope), soil material (e.g., permeable or not), land cover and vegetation, climatic factors, etc.

The water level h_r refers to the river closest to the location under exam, when following the hydrological flow path[8] ('r' in the subscript stands for river). It is calculated as a function of the contributing area (i.e., the area of the upstream water basin that drains to this point in the river), using the hydraulic scaling function[9]:

$$h_r \approx A_r^n \quad \text{Equation 2}$$

where h_r [m] is the water level in the nearest river element, A_r [km^2] is the contributing area to this river element, and n is a scaling exponent [dimensionless].

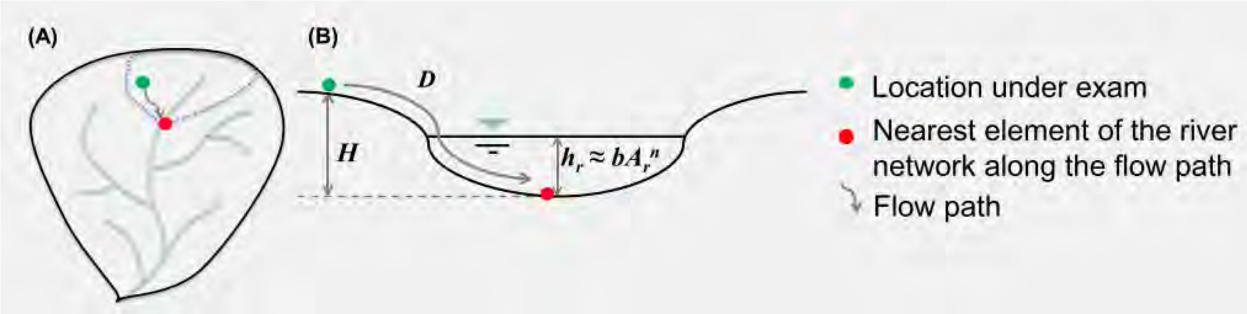

Figure 6: Schematic for the Geomorphic Flood Index (GFI), calculated as GFI = ln(h_r/H). (A) Representation in watershed. (B) Conceptual model of river cross section. Figure by (Samela *et al.*, 2017)**; creative commons license CC BY-NC-SA.**

Using Equation 1, the GFI is calculated for each grid cell of a water basin, resulting in a raster of (dimensionless) GFI values ranging typically from approximately -12 to +5.

4.1.2 Calibration Method

Following the development of GFI grid, existing flood maps (that ideally have been developed using hydraulic modelling) are used for calibration. For this, a threshold of the GFI is identified, for which all values above the threshold are considered flood prone, and all values below the threshold are considered not flood prone. The threshold is adjusted such that overlap between areas identified as flood prone by the GFA tool resemble the flood extents from the hydraulic flood maps used for comparison. The calibration is therefore focused on areas with existing flood maps, and the identified threshold is then applied to the entire watershed.

Depending on the AEP of the calibration flood maps, the resulting flood prone areas developed for the greater watershed approximate the areas of potential flooding that could be expected under the same AEP. However, this approximation needs to recognize the important limitations of the approach, recognizing that no rainfall-runoff processes are explicitly considered in this geomorphic approach.

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[8] The hydrological flow path is the route that water would follow across the landscape from a point on, for instance, a hillslope to the river at the foot of the hill.

[9] The hydraulic scaling function assumes that the water level in a river is proportional to the size of the contributing area, and is widely used throughout hydrology.

4.2 Input Data

4.2.1 Digital Elevation Model (DEM)

The principal input for the GFA analysis is a Digital Elevation Model (DEM), which provides information on the geomorphological characteristics of the watersheds. High-resolution DEMs are beneficial for the analysis as they allow detailed capturing of topographical features. However, the study area also has a large extent, resulting in a trade-off between DEM resolution and computer run times. Thus, it would not have been feasible to use LiDAR data for this project.

Therefore, the Canadian Digital Elevation Model (CDEM)[10] was used, and the DEM was downloaded at the five spatial resolutions that were available (0.75, 1.5, 3, 6, and 12 arc-seconds) for the study area to allow testing for effects of the DEM. Characteristics of the DEM resolution, which were used for the final generation of the GFA flood prone areas, are given in Table 1, and the DEM is plotted in Figure 7.

Table 1: Digital Elevation Model characteristics used as input for the GFA.

Characteristic	Value
Spatial Resolution in arc-seconds	0.75
Spatial resolution in meters (approximately)	~15 x ~23
CRS (Coordinate Reference System)	EPSG 4617 – NAD 83 (CSRS)
Vertical Datum	CGVD28 (Canadian Geodetic Vertical Datum of

[10] Canadian Digital Elevation Model (CDEM), Government of Canada: http://maps.canada.ca/czs/index-en.html. Accessed in March 2019.

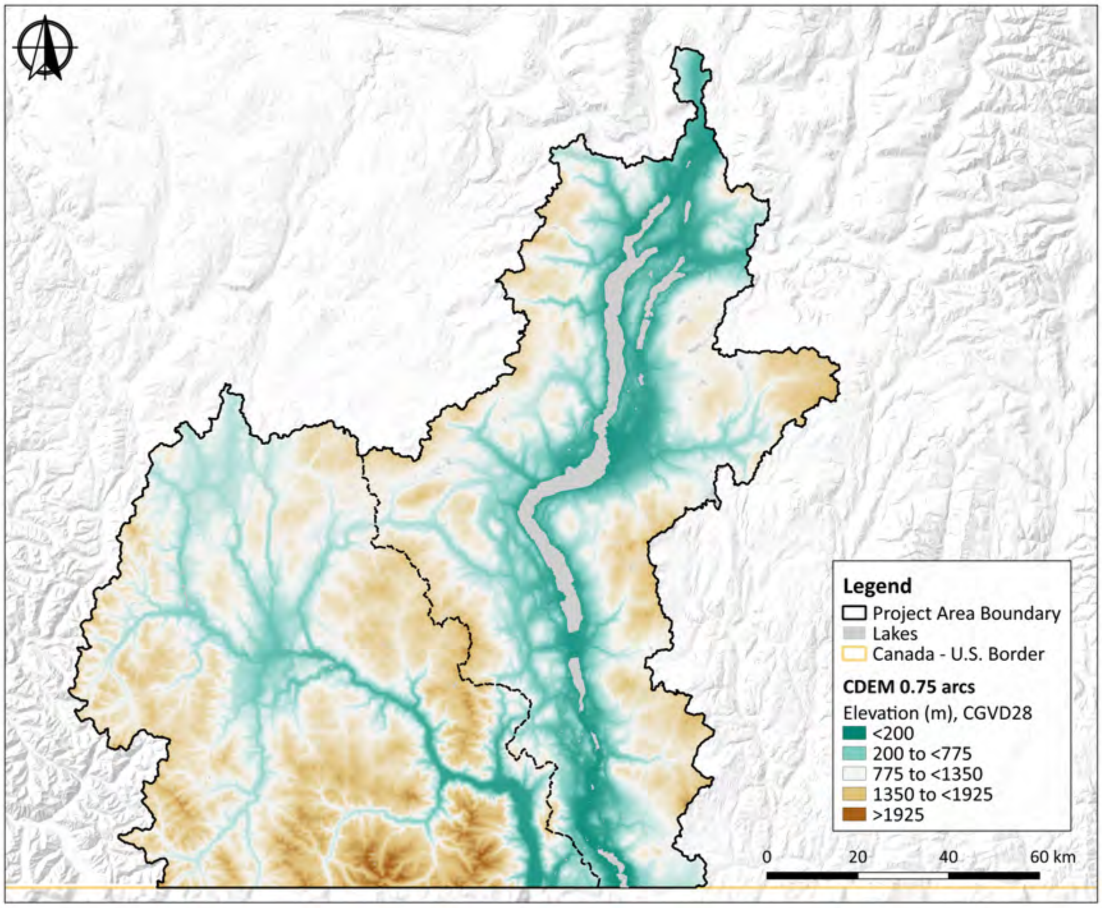

Figure 7: Elevation in metres (CGVD28), based on CDEM 0.75 arc-second.

4.2.2 DEM Pre-processing

The GFI is calculated based on terrain analysis of the DEM – however, first the DEM has to be pre-processed. Specifically, the DEM has to be prepared so that each cell of the DEM has a downslope neighbour cell to which water can 'flow' without errors (this is called 'hydrological-conditioning' of a DEM) (Samela *et al.*, 2018). DEMs typically have spatial irregularities and errors that sometimes do not correctly reflect the actual conditions, for instance, so-called 'sinks' and 'depressions' which would impede flows. These have to be filled to allow continuous hydrological flows. A 'Fill Sink' algorithm was used that allowed the smoothing of these 'sinks' and created a hydrologically-conditioned DEM.

Next, a 'flow direction matrix' was created from the hydrologically-conditioned DEM, which is required as input for the GFA tool (Figure 8). For this, a single-direction flow algorithm called 'D8' was used, where each raster cell is associated with a direction in which water flows out of the cell, depending on the elevation of the 8 surrounding cells. Using the results, a 'flow accumulation matrix' was created, which estimates the upslope contributing area for each raster cell, based on the flow paths presented in the flow direction matrix. These four raster datasets (original DEM, hydrologically-conditioned DEM, flow direction matrix, and flow accumulation matrix) constituted the input data for the analysis.

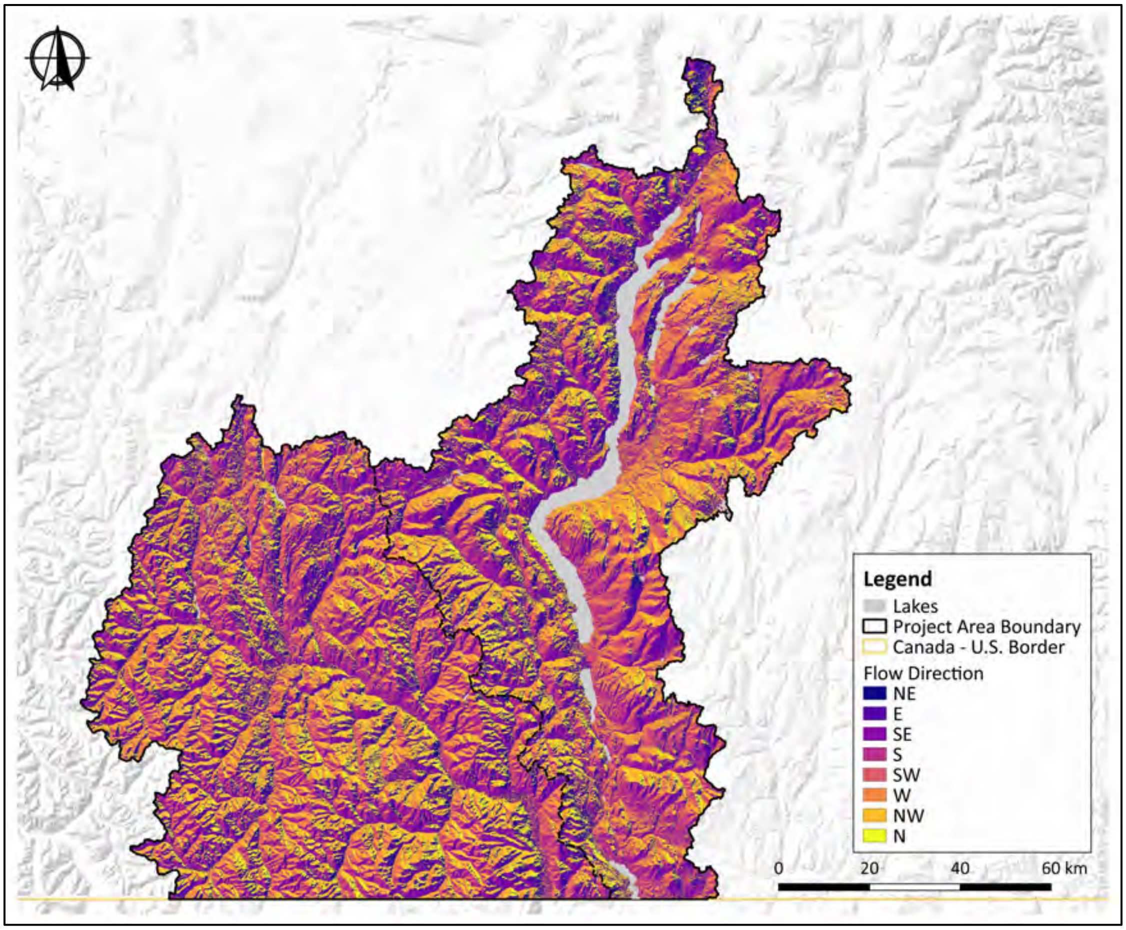

Figure 8: Flow Directions based on the 0.75 arc-second CDEM.

4.2.3 Floodplain Maps for Calibration

The flood extents from hydraulic modelling studies across the study region were used for calibration. Specifically, the FDRP floodplain maps were used, which were available for the Tulameen River at Tulameen, the Tulameen and Similkameen Rivers at Princeton, the Similkameen River at Keremeos, the Okanagan River from Penticton to Osoyoos, and Mission Creek (BC Ministry of Environment, 1981, 1984, 1993, 1995b, 1995a). The flood extents for the FDRP maps showed the 0.5% AEP plus a 0.6 m freeboard allowance. Further, the results from the 2010 Mill Creek study (Associated Engineering Ltd, 2010), for which also a 0.5% AEP flood plus a 0.6 m freeboard was mapped, as well as the City of Armstrong flood mapping from 2018 (0.5% AEP) (Interior Dams Incorporated, 2018) were used. For more details on these studies, see Section 2.

Considering that all of these studies referred to the 0.5% AEP, the calibrated flood prone area is approximately equivalent to this likelihood, which was termed the 'moderate flood magnitude' scenario (see also Section 4.4).

4.3 Parameterization and Evaluation

4.3.1 Initial Sensitivity Analysis

The GFA tool has a number of parameters, where the values can be varied to achieve optimal fit of the GFA-generated flood extents to existing flood maps. These parameters include a “drainage network identification threshold” (which essentially determines for which order of rivers the flood extents should be mapped), a hydraulic scaling exponent (used as a parameter in Equation 2 to estimate approximate water level in rivers from the upstream contributing area), and the GFI threshold (a linear boundary between areas recognized as flood prone, and areas recognized as not flood prone).

As a first step for determining the parameter values of best fit, a sensitivity analysis was conducted where the value of one parameter was varied by plus/minus 50% of its default value, while leaving the other parameter values constant at default. The total flood prone area was then calculated and described in terms of variance from the flood prone area that was determined by using the default values alone (Table 2).

The results show that the GFA-generated flood prone area is most sensitive to the GFI threshold (i.e., the mapped flood-prone area increases or decreases a lot when this threshold is changed), which reflects that the GFI is the main calibration parameter of the GFA tool. In contrast, changes were smaller for the hydraulic scaling exponent, and minor for the drainage network identification threshold.

Table 2: Sensitivity Analysis for the GFA tool in the study area.

Parameter	Default Value	Default Value + 50%		Default Value + 50%	
		Value	% area change relative to default	Value	% area change relative to default
Drainage network identification threshold	10,000	15000	-4	5000	+7
Hydraulic Scaling Exponent	0.3544	0.5316	+64	0.1772	-31
GFI threshold	-0.53	-0.795	+433	-0.265	-69

4.3.2 Calibration

In the next step, the parameters were adjusted during calibration within the GFA tool and various combinations of parameter sets were tested with a total of 60 different runs of the GFA, with the goal to achieve best fit of the GFA flood extents to the existing hydraulic modelled floodplains. A full Monte-Carlo-type analysis, which would consist of testing hundreds of parameter combinations, was not possible as, considering the large extent of the area and the many hours of run-time for each of the tested parameter combinations, such an analysis was out of the scope of this high-level hazard assessment. In addition to the parameter values, the five different DEM resolutions were also tested (Table 3).

Below are some more details on the calibration process and findings:

- The calibration was started using the lowest resolution DEM (6 arc-seconds), and in a step-wise fashion, the resolution was increased to the highest DEM resolution of 0.75 arc-seconds.

- The GFA tool includes two methods to define the drainage network and the order of streams that are included into flood mapping (i.e., to define if are flood extents mapped for even small creeks, or only for bigger streams and rivers). One method (the 'Channel_FAt' method) uses a 'drainage network identification threshold' for the size of the upslope contributing area of a raster cell that is considered for flood prone areas. Thus, very small upstream tributaries can be excluded from mapping, which proved to be necessary for this analysis. The other method (called 'Channel_ASk') yielded challenges for the study area, and often the software program would not run when using this method, especially for the higher resolution DEMs.
- For the hydraulic scaling relation exponent, the default GFA value (0.3544) worked best. This value was developed by Samela et al., (2017) based on an analysis across many rivers of North America. Further, there was not sufficient good hydrometric data available to produce a hydraulic scaling parameter specific for the study watersheds.
- Lastly, the main calibration parameter, the GFI, was adjusted. Using the previously discussed parameters, the GFA tool calculates the GFI, an index which ranges from approximately -12 to +5 (Figure 9). The GFI threshold then defines the linear boundary for areas recognized as flood prone, and areas recognized as not flood prone. The GFI was adjusted to provide the best fit of the GFA flood prone areas to the existing (FDRP and modern) floodplain maps.

An overview of the parameter ranges that were explored is given in Table 3, as well as the final calibrated parameter set, which was used to define the 'moderate magnitude flood' scenario.

For definition of the final parameter set for the 'moderate magnitude flood' scenario, a conservative approach was used. Thus, it was aimed to capture the outer boundaries of the FDRP floodplain mapping, while on the other hand also balancing that flood extents were not over-estimated by large areas.

Table 3: Parameters (and DEM resolution) tested for the GFA analysis, including starting value, tested range, and the final value which was applied for the calibrated layer ('moderate magnitude flood').

Parameter	Starting Value	Tested Range	Final Value
Drainage network identification method	'Channel_Ask' (default)	'Channel_Ask' method; 'Channel_FAt' method	'Channel_FAt' method
Drainage network identification threshold	10,000 (default)	500 to 100,000	10,000
Hydraulic scaling relation exponent	0.3544 (default)	0.28 to 0.8	0.3544
DEM resolution (arc-seconds)	6	0.75, 1.5, 3, and 6	0.75
GFI threshold	-0.53 (default)	-1.0 to -0.1	-0.29

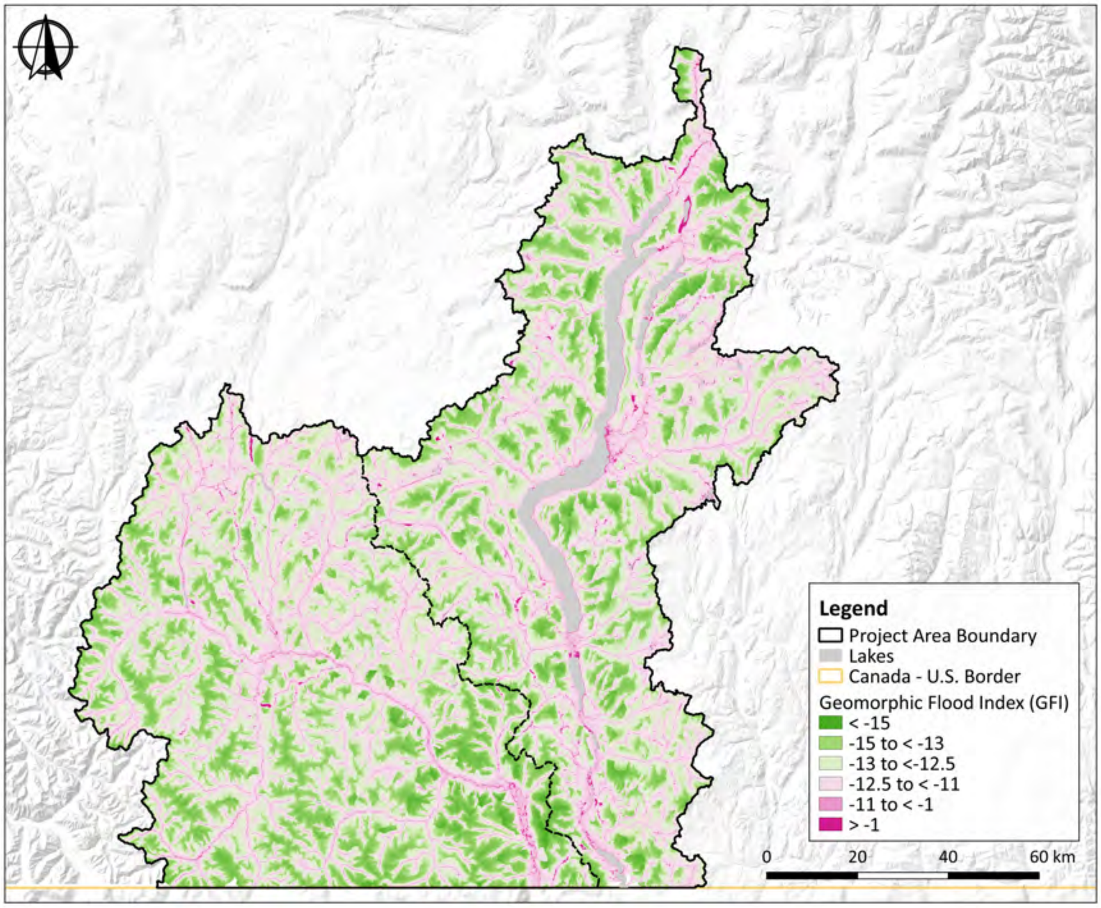

Figure 9: Geomorphic Flood Index (GFI) for the project area.

4.3.3 Evaluation using FDRP and Recent Hydraulic Flood Maps

For evaluation of the calibrated GFA flood prone area mapping, the results were compared to existing floodplain maps that had been obtained via hydraulic modelling, i.e., to the FDRP floodplain maps (Figure 10, Figure 11), and more recent mapping from Armstrong and Mill Creek (Figure 12).

Overall, the GFA was able to capture the flood extents from the hydraulic modelling well, and the flood prone area extents were similar for both methods.

However, some limitations are obvious, and in some locations, the GFA showed slightly larger or smaller flood extents than obtained from hydraulic modelling. It is important to remember here the different mapping methodologies, and the limitations and uncertainties contained in both: For the FDRP floodplain mapping, a 1-dimensional hydraulic model was used, and floodplain extents were obtained by extending modelled flood water levels in rivers to the nearest topographic elevation contour line. This resulted, in some instances, in less fine-scaled spatial variability than what the DEM-based GFA indicated (see for instance Figure 10c). Furthermore, the FDRP floodplain mapping did not consider the hydraulics of tributaries – while the GFA considered flood extents for all bigger watercourses. Thus, at most confluences of tributaries with the main river system, the GFA showed larger flood extents than the FDRP mapping.

As the GFA is based on geomorphology, it typically did not portray channelized and modified river systems. Instead, a larger flood prone area was captured extending beyond the channelized river system. This can be seen for the Okanagan River at Penticton, where the river system is highly managed with dikes (Figure 11a), and Deep Creek at Armstrong, where Deep Creek is partially channelized through the city (Figure 12a). The Armstrong study was also limited to the city extents, and thus did not include the larger flood extents shown by the GFA.

Another limitation was that the GFA calibration needed to represent both the Similkameen and Okanagan watersheds, as not enough flood mapping existed to individually calibrate sub-watersheds. The overall results were however considered satisfactory, as the main shape and extent of the hydraulic flood maps were predominantly captured.

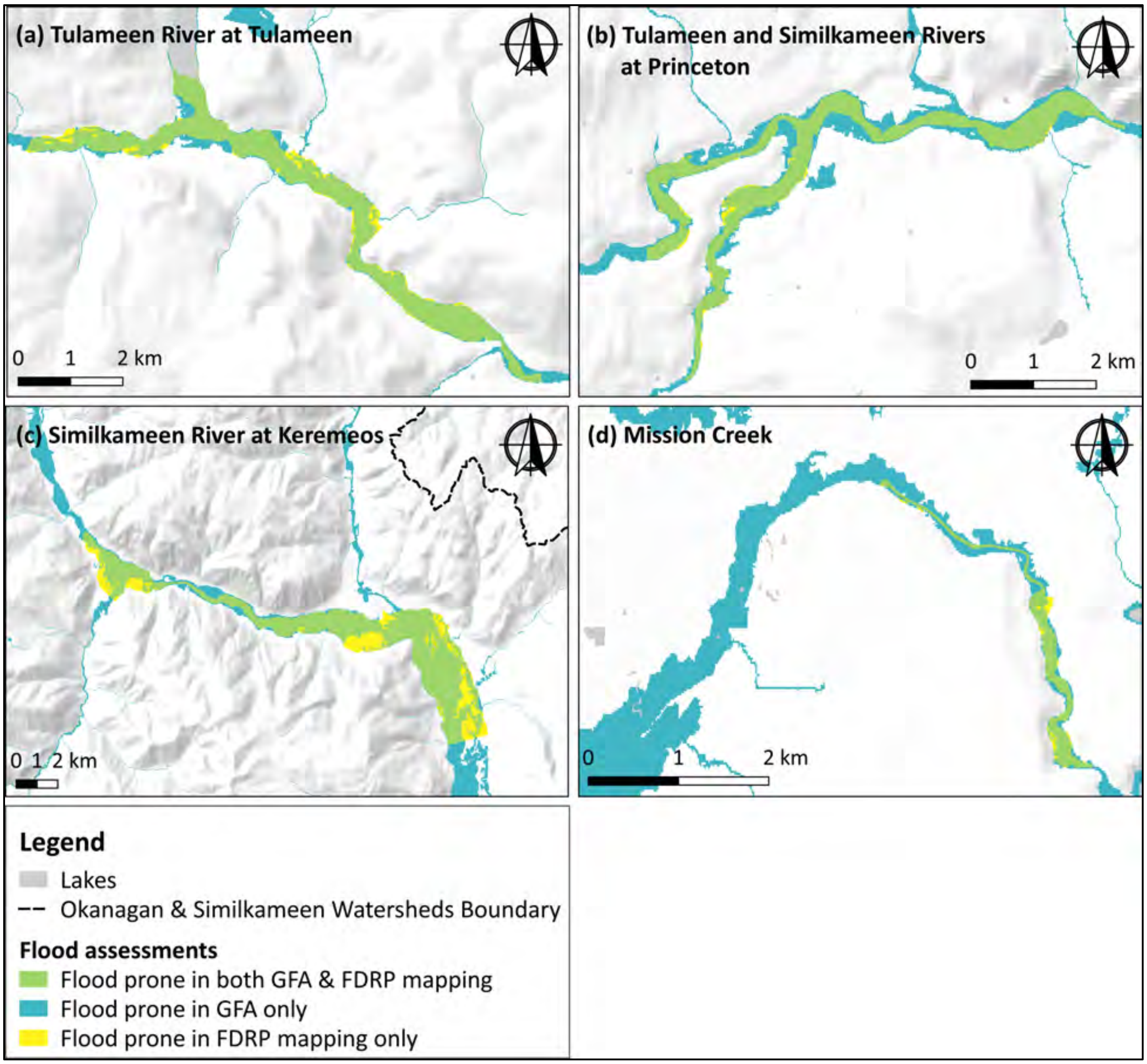

Figure 10: Comparison of flood prone areas identified by the GFA and the FDRP floodplain mapping for the Tulameen River, Similkameen River and Mission Creek.

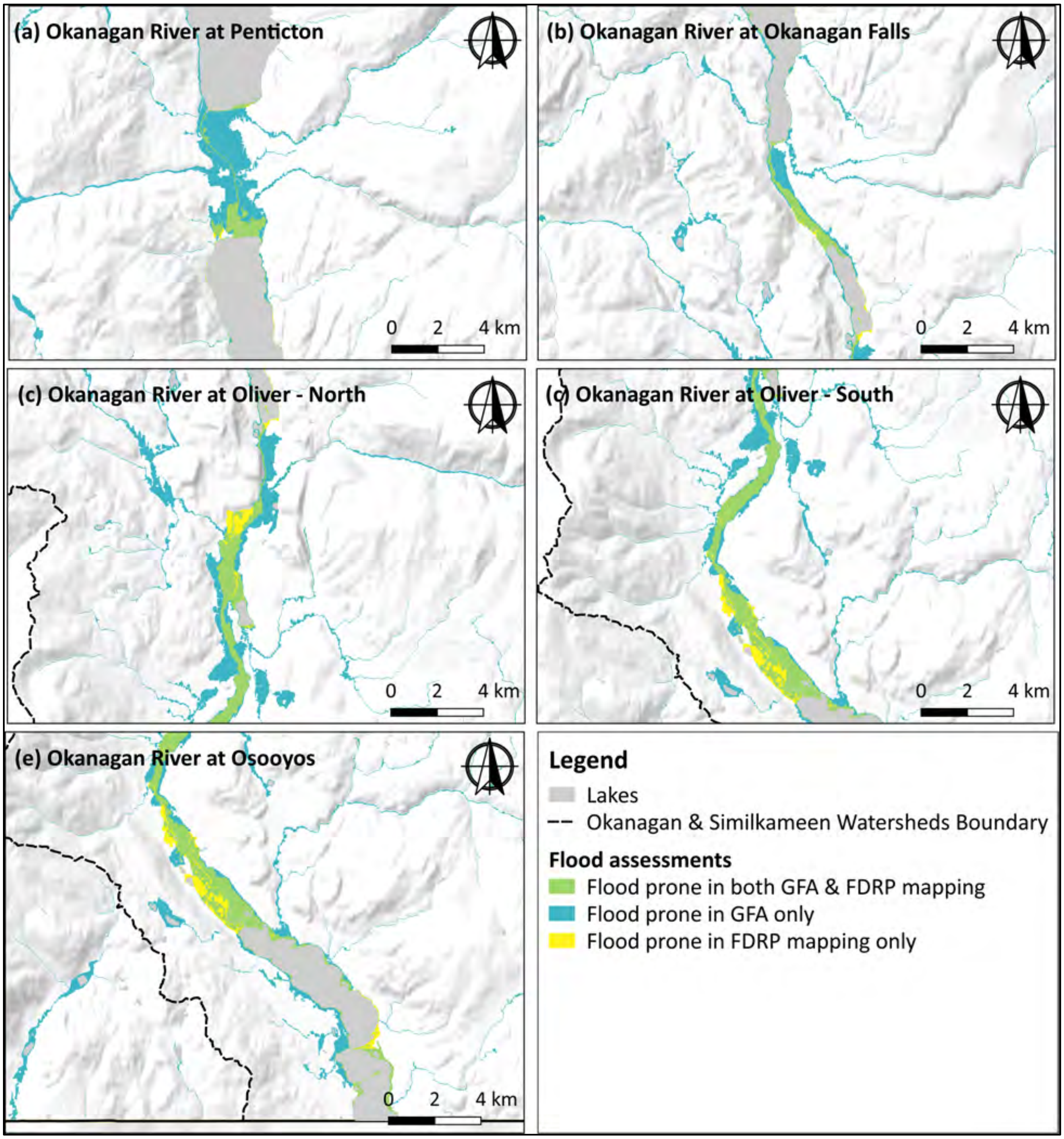

Figure 11: Comparison of flood prone areas identified by the GFA and the FDRP floodplain mapping for the Okanagan River.

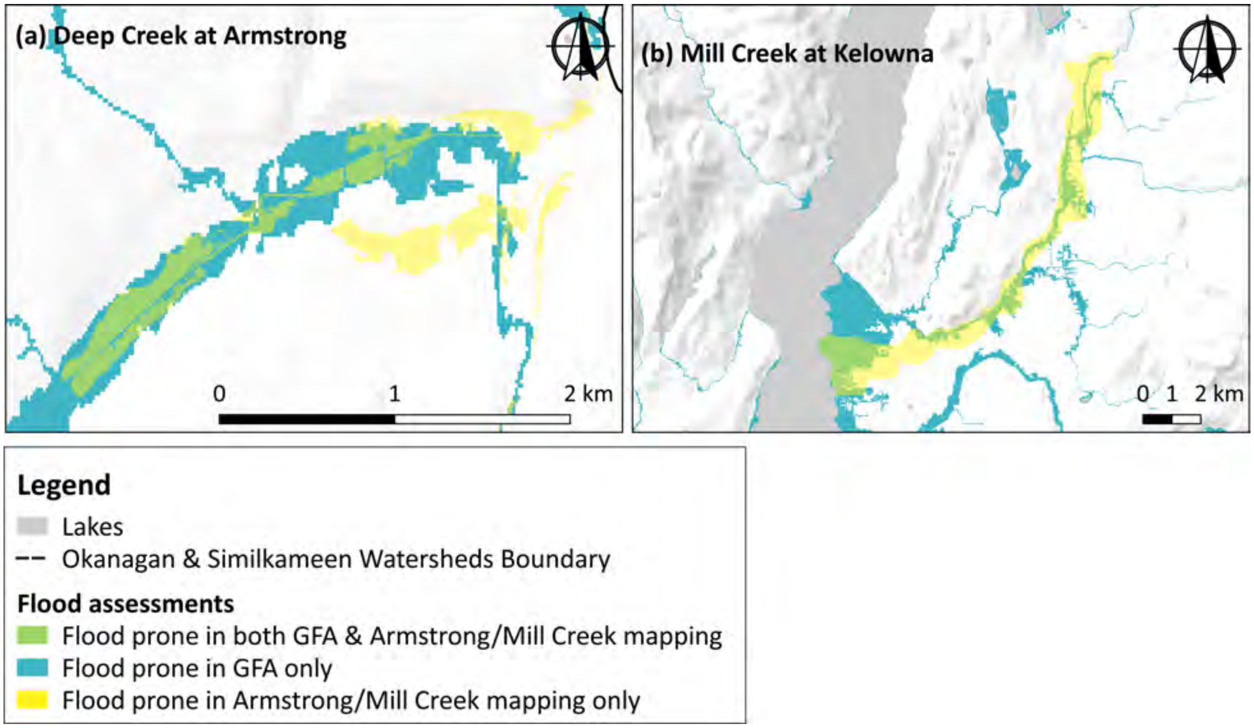

Figure 12: Comparison of flood prone areas identified by the GFA and the Armstrong/Mill Creek mapping flood prone areas for the Tulameen River, Similkameen River and Mission Creek.

4.4 Flood Hazard Magnitude Scenarios

To allow a broad assessment of potential flood consequences, flood prone areas were developed for low, moderate, and high magnitude flood scenarios using the GFA tool. A low magnitude flood may result in less damage, but as it occurs more frequently; cumulative damages over years could add up. On the other end of the spectrum, a high magnitude flood occurs more rarely, but would result in catastrophic consequences. While a full probabilistic risk assessment would require more flood hazard magnitude scenarios and was out of scope for this high-level assessment, the three scenarios can be used to compare possible flood consequences between different magnitude hazards.

4.4.1 Scenario Assumptions

The FDRP mapping had been conducted solely for the 0.5% AEP (plus freeboard), and limited hydraulic flood mapping existed for any other flood magnitudes (apart from the Armstrong study, see discussion below under the low magnitude flood scenario). Below, the assumptions for the scenarios are discussed.

Moderate Flood Magnitude Scenario

The moderate magnitude flood scenario represented the calibrated GFA flood prone area layer, which was approximately equivalent to the 0.5% AEP, plus a 0.6 m freeboard (the freeboard was included within the FDRP maps used for calibration).

High Flood Magnitude Scenario

To allow gauging potential flood extents for a high magnitude scenario, global floodplain mapping ('Global Flood Map') by FMGlobal was used, which provides low spatial resolution, global scale floodplain mapping for 1% and 0.2% AEP floods[11]. The flood maps are based on a physical model (the Hillslope River Routing catchment-based hydrologic model), a 2D hydrodynamic model on a 90 x 90 m resolution grid, using global land cover and precipitation layers, and considering processes such as evapotranspiration, snowmelt and terrain (FMGlobal, 2019). However, as the model is developed on a global scale, it only includes watersheds over 101 km^2, and its relatively low spatial resolution leads to some misrepresentations in the study watersheds. The floodplain mapping is also proprietary and not directly accessible for analysis. Thus, it would not have been possible to use this layer directly for flood risk analysis.

However, images of selected areas of the 'Global Flood Map' for the study area were georeferenced, and the extent of the 0.2% AEP 'Global Flood Map' flood scenario was used as guidance for the high magnitude flood scenario. It is important to highlight the different methodologies for the 'Global Flood Map' and the GFA analysis explained in the previous sections, as each tool comes with its own limitations and uncertainties.

The approach to defining the high magnitude flood scenario was based on capturing all 'Global Flood Map' 0.2% AEP flood extents. Therefore, the high magnitude flood scenario typically shows a flood extent that is consistently larger than the 0.2% AEP flood scenario in all locations. Note that the approach does not relate the high magnitude flood scenario conclusively with one specific AEP flood extent.

To obtain the flood prone area for this high magnitude scenario, the same GFA model parameters as calibrated for the moderate magnitude scenario were used, but changed the GFI threshold from -0.29 to -0.43 (difference of 14 GFI units), resulting in the larger flood prone area extents.

Low Flood Magnitude Scenario

No appropriate flood maps were available within the project area that could be used for calibration of a low magnitude flood scenario. For the purpose of the risk assessment, the objective was to estimate the flood extents for a scenario that was more frequent than the 1% AEP provided in the FMGlobal mapping. And while a 5% AEP flood extent was available for the Armstrong study, it was not suitable for use. As discussed in Section 4.3.3, Deep Creek in Armstrong is heavily managed and partially channelized, and thus, did not represent geomorphic flood prone areas well. It also constituted a very small part of the study area.

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[11] FMGlobal flood map: https://www.fmglobal.com/research-and-resources/global-flood-map/flood-map

Therefore, a symmetrical scaling approach was used, and the same number of GFI units was applied proportionally around the moderate magnitude GFI threshold, resulting in a GFI threshold of -0.15 for the low magnitude scenario. This resulted in flood prone area extents that were larger than the natural river boundary, but that were still substantially smaller than flood extents for the moderate magnitude scenario.

4.4.2 Flood Scenario Results

Results for the three flood magnitude scenarios are shown for the project area in Figure 13, as well as in more detail for example sections of the Tulameen and Similkameen River (Figure 14), the Okanagan River (Figure 15), and Deep Creek and Mill Creek (Figure 16). More detailed flood hazard mapping is also provided in the Map Book.

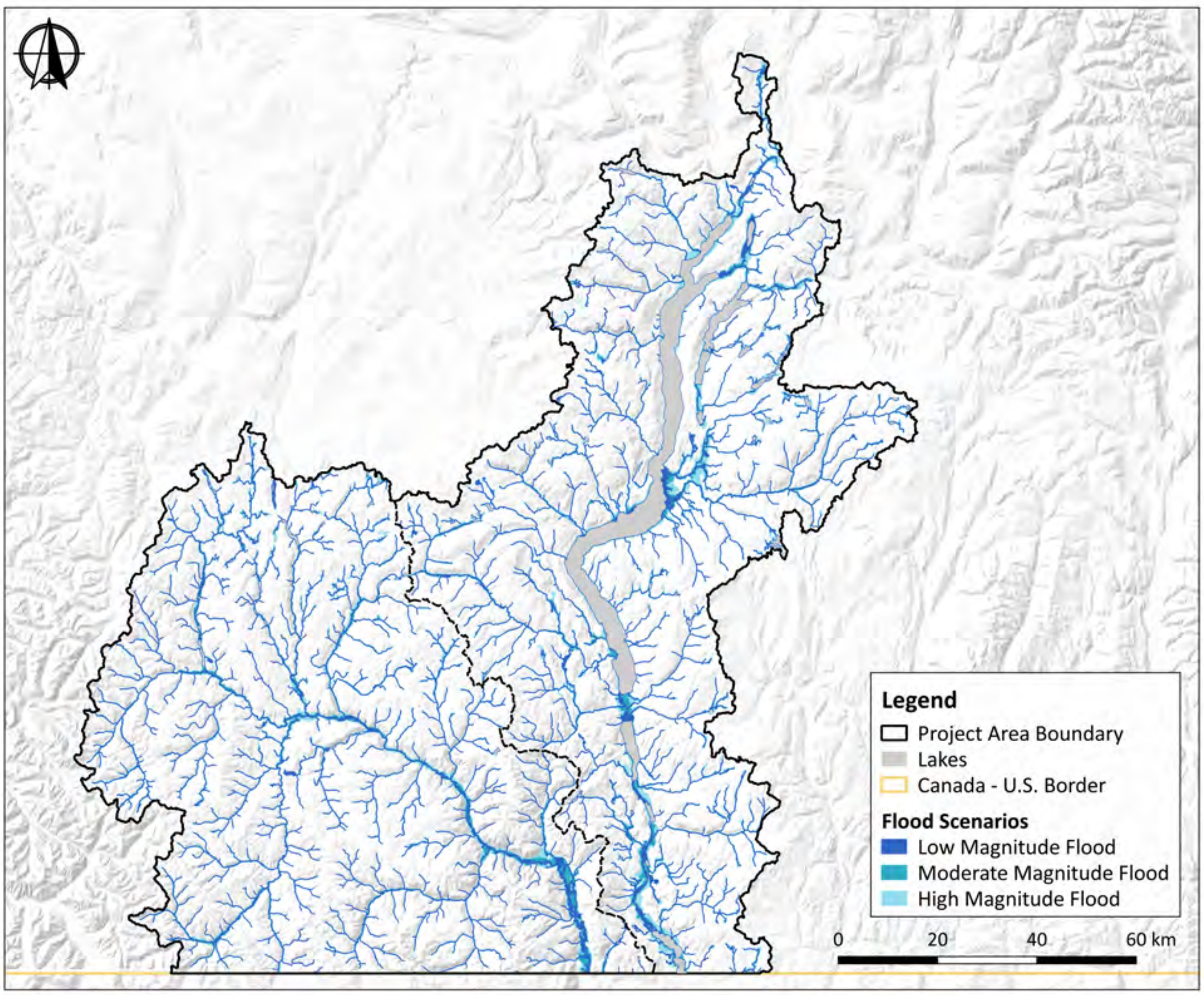

Figure 13: Low, moderate, and high magnitude flood scenarios for the Similkameen and Okanagan watersheds, as determined by the GFA analysis.

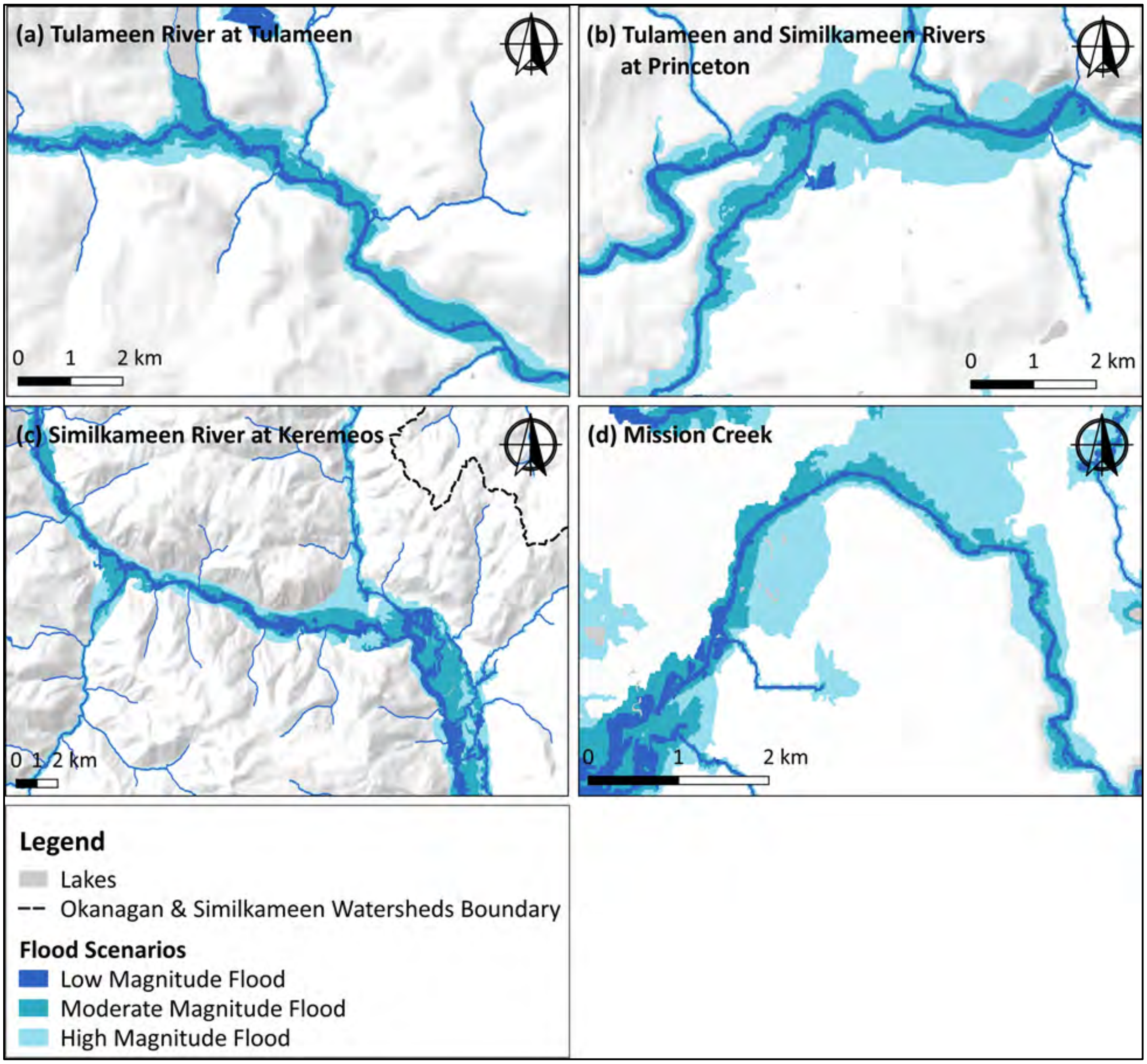

Figure 14: Low, moderate, and high magnitude flood scenarios for the Tulameen River, Similkameen River, and Mission Creek, as determined by the GFA analysis.

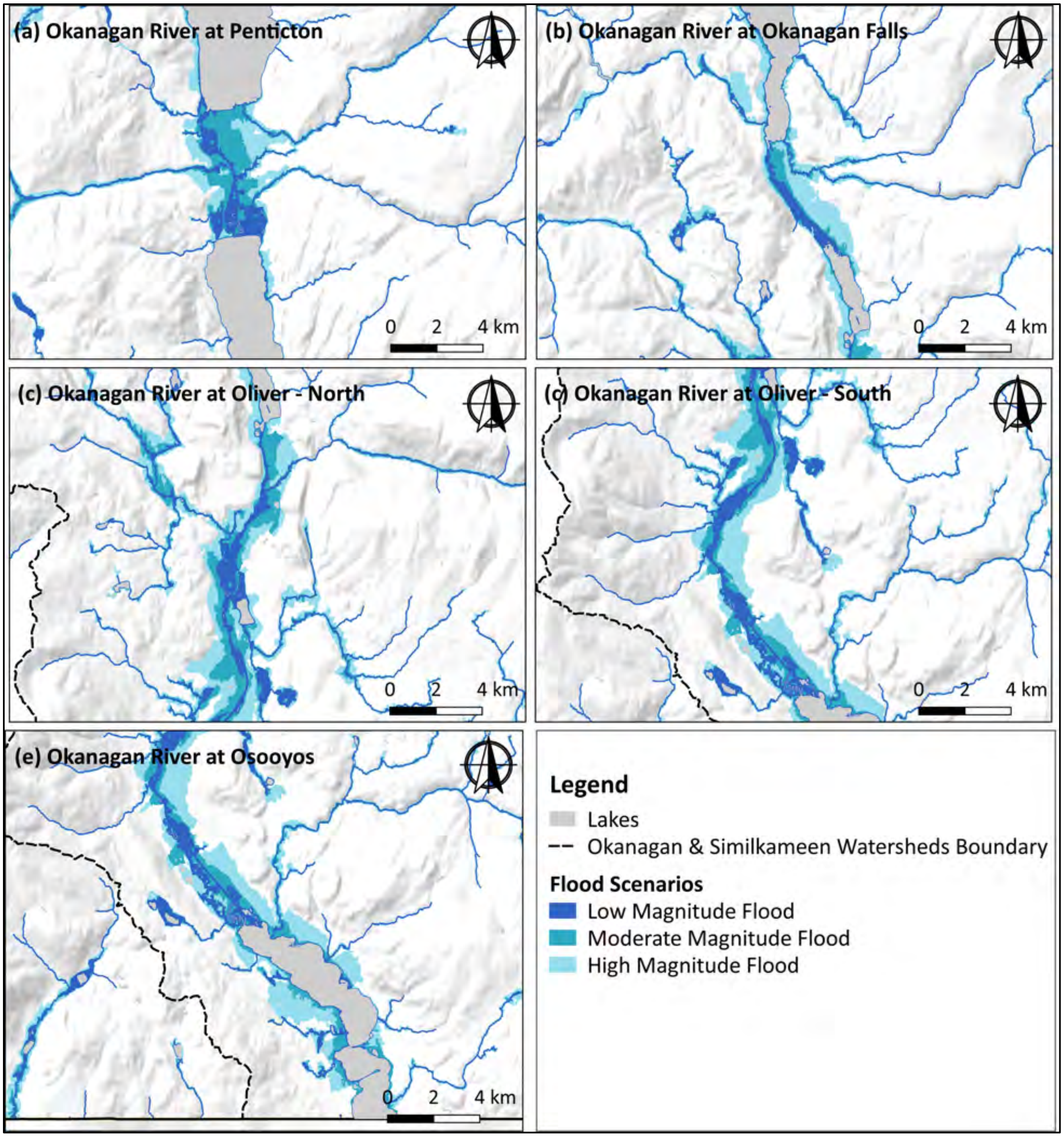

Figure 15: Low, moderate, and high magnitude flood scenarios for the Okanagan River, as determined by the GFA analysis.

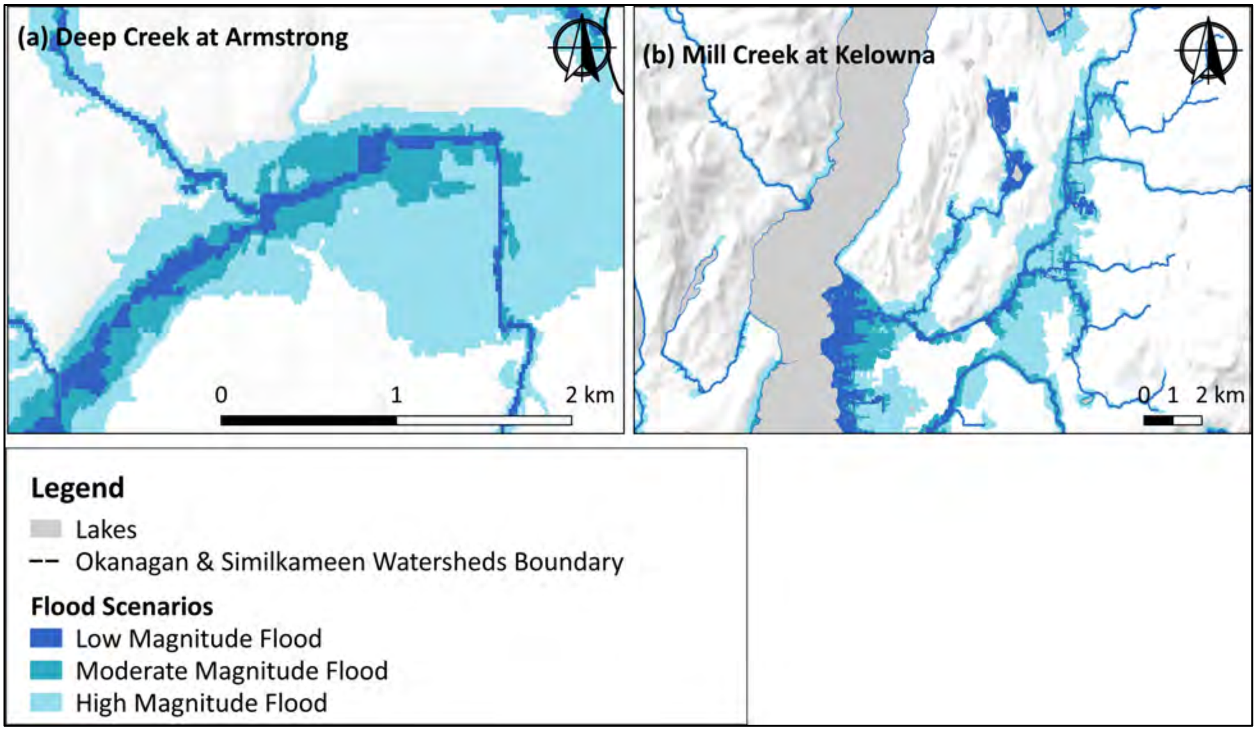

Figure 16: Low, moderate and high magnitude flood scenarios for Deep Creek and Mill Creek, as determined by the GFA analysis.

Table 3 provides summary information for each of the three flood scenarios, including the process and data source that were used to calibrate and define the hazard magnitude extents. An estimate of the associated AEP for the moderate magnitude scenario is also provided. For the high magnitude scenario, it can only be indicated that the AEP is smaller (i.e., its probability of occurrence is lower) than the 0.2% AEP. For the low magnitude scenario, it was not possible to indicate an AEP, as no low magnitude scenarios were available for calibration.

Table 4: Flood hazard magnitude scenario characteristics.

Scenario	Approximate AEP	Description	GFI value	Source
Low	n/a	Frequent	-0.15	GFI unit difference applied symmetrically around moderate magnitude GFI, as no appropriate low magnitude flood maps were available within the project area.
Moderate	0.5%, plus 0.6 m freeboard	Moderate	-0.29	GFA model calibration to FDRP maps in the project area, that have a 0.5% AEP, plus 0.6 m freeboard.
High	Smaller than 0.2%	Rare	-0.43	GFI adjusted using selected project areas of the Global Flood Map.

Lastly, for risk scoring as part of the risk assessment, each flood scenario needed to be associated with a likelihood score. For details on risk scoring methods and assumptions, please see the main Quantitative Report. The approximate AEPs in Table 4 were used to determine likelihood scoring in the risk assessment, based on the approximate AEP ranges in Table 5. It is important to emphasize that while AEPs where used as guidance within the process of defining likelihood scores, the scenarios are referred to in terms of hazard magnitudes (i.e. low, moderate, and high). The flood scenarios should not be associated with AEPs for the purposes of this risk assessment study, based on the limited data that were available for the analysis.

Table 5: Approximate AEP ranges used for likelihood scoring in the risk assessment.

Flood Magnitude Scenario	Approximate Annual Exceedance Probability (AEP) Range	Available Supporting Data?
Low	3.3% to <63% per year	No
Moderate	0.33% to <3.3% per year	Yes
High	0.033% to <0.33% per year	Yes

4.5 Limitations

The geomorphological approach of the GFA does not consider hydrological processes of runoff generation (such as, precipitation, infiltration, evapotranspiration, surface and subsurface runoff). In addition, the geomorphological analysis does not account for hydraulic processes within the river system, and interactions with infrastructure such as flood defences. Thus, the approach can only provide information for areas that *might* be prone to flooding.

Calibration of the GFA was challenging for low (more frequent) and high (rare) magnitude scenarios, as existing hydraulic flood mapping for frequent and rare flood scenarios were limited. Thus, these scenarios can only allow gauging of the potential flood hazards and risks, but results should be used with caution. The flood prone areas determined with the GFA should therefore only be used for a high-level analysis, and not be used for design and other purposes.

Nevertheless, the flood prone areas determined in this flood assessment can support high-level flood risk assessments and guide prioritisation of areas where detailed hydraulic modelling might be targeted in the future. Further, the flood mapping outputs from this approach cover the entire project area, whereas previous floodplain mapping had solely focused on population centres.

5 Conclusion

An understanding of flood hazard areas was required for this risk assessment as a basis to qualitatively assess impacts and to quantitatively assess consequences from this natural phenomenon. The flood areas were defined iteratively as the project progressed.

During the early stages of the project, available flood-related information and maps were reviewed, including outputs from regional-scale studies and detailed and local-scale hydraulic modelling. For the engagement activities, preliminary flood extents were developed based primarily on expanding a method (i.e., the geology and soil mapping method) that had been applied within one region of the project area (i.e., the RDCO). The maps resulting from this preliminary flood assessment covered the project area and were suitable to help participants understand, at a high-level, where flooding had recently occurred or could occur in the future. The maps were used in the Qualitative Study, in conjunction with modelled preliminary debris flow hazard areas (see Appendix C of the Quantitative Study).

For the quantitative risk assessment component of this project, flood scenarios were developed that were representative of low, moderate, and high flood magnitudes. The flood extents resulting from these scenarios were developed using a more detailed method (i.e., the geomorphic flood area (GFA) method) consistently across the project area. The maps were used in the Quantitative Study, in conjunction with the modelled debris flow susceptibility and generalized flow paths mapping (see Appendix C of the Quantitative Study), and the approach thus allowed to spatially quantify flood consequences associated with a high-level understanding of flood likelihoods. While there are limitations to the GFA approach, the obtained quantitative risk assessment results can guide future prioritisation of studies, including identifying where more detailed flood and debris flow mapping may be required.

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Syilx Okanagan Flood and Debris Flow Risk Assessment

Report 4 of 4 – Quantitative Study

Appendix C: Debris Flow Hazard Assessment (Palmer)

PALMER ENVIRONMENTAL CONSULTING GROUP INC.

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Okanagan Basin Debris Flow Hazard Overview Assessment

PECG Project #
170502

Prepared For
Ebbwater Consulting Inc.

June 27, 2019

PALMER ENVIRONMENTAL CONSULTING GROUP INC.

June 27, 2019

Robert Larson, M.Sc., P.H., A.Ag.
Hydrologist
Ebbwater Consulting Inc.
510 - 119 W Pender St
Vancouver, BC, V6B 1S5

Dear Mr. Larson:

Re: Okanagan Basin Debris Flow Hazard Overview Assessment
Project #: 170502

Palmer Environmental Consulting Group Inc. is pleased to present Ebbwater Consulting Inc., working on behalf of the Okanagan Nation Alliance, with the results of our debris flow hazard overview assessment for the Okanagan Basin. Appended to this report is a geodatabase file containing a debris flow initiation susceptibility model and a generalized debris flow path model for use in the flood and debris flow risk assessment.

Please contact Derek Cronmiller at 867 689 5776 or derek@pecg.ca if you have any questions regarding the contents of the report.

Yours truly,
Palmer Environmental Consulting Group Inc.

Derek Cronmiller, P.Geo.
Geoscientist

Robin McKillop, M.Sc., P.Geo.
Principal, Surficial Geologist

PALMER ENVIRONMENTAL CONSULTING GROUP INC.

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1. Introduction

Palmer Environmental Consulting Group Inc. (PECG) is pleased to provide Ebbwater Consulting Inc. (Ebbwater), working on behalf of the Okanagan Nation Alliance (ONA), with the results of our debris flow hazard overview assessment for the Okanagan Basin, south-central British Columbia. Mountainous portions of the watersheds comprising the Okanagan Basin contain hazard-prone areas based on their steep slopes and history of landslides and flooding. The debris flow hazard overview assessment described herein has been completed to help advance the initiative of the ONA to improve its understanding of natural hazards and ultimately help reduce associated risk to its member communities. The results from this desktop-based debris flow study establish a foundation for Ebbwater's risk assessment. Timothy Smith P.Geo., Eng.L., representing Westrek Geotechnical Services Ltd. (Westrek), acted in an advisory role on this project during the initiation of this project and shared Westrek's proprietary landslide database for the purpose of validating the debris flow initiation susceptibility model.

1.1 Definitions

Clearwater flood: An extreme hydrologic event where sediment comprises less than 20% of the discharge by weight (Wilford et al., 2004). These events are commonly caused by moderate to heavy or prolonged rainfall, melting snow, or a combination of the two. This term is favoured over "flood" for clarity.

Debris flood: A channelized flood of sediment-laden water, where sediment concentration can range from 20-47% by volume (Wilford et al., 2004). Peak discharges of debris floods be twice that of clearwater floods at the same hydrologic setting (Hungr et al., 2001). Debris floods are not considered a landslide.

Debris flow: A rapid, high-density mass movement of saturated debris. Debris flows can occur on open slopes or be channelized in a steep gully. A debris flow may initiate as a debris slide or rockslide that becomes channelized in a gully, and enlarges through entrainment of surficial material, organic debris and water. Debris flows are commonly triggered by intense or prolonged precipitation and can have peak discharges up to 40 times greater than clearwater floods at the same hydrologic setting (Hungr et al., 2001). Debris flows may transition to debris floods through addition of water in tributaries (Wilford et al., 2009) or where confinement is lost.

Debris slide: A sliding mass of unconsolidated surficial material. May transition into a debris flow through confinement.

1.2 Study Area

The study area comprises the entire 15,500 km^2 Okanagan Basin in south-central British Columbia (Figure 1.1). Major population centres in the study area include Kelowna, West Kelowna, Vernon, and Penticton. Many smaller centres and rural residential districts also populate the region, giving the Okanagan Basin a total population of over 360,000.

1.2.1 Physiography

The study area straddles multiple physiographic regions within British Columbia's southern Interior Plateau. These regions include the Cascade Mountains, Thompson Plateau, Okanagan Valley, and Shuswap and Okanagan Highlands (Mathews, 1986). Each physiographic region has a unique geologic history that has resulted in distinguishing landforms. The Okanagan Valley trends generally north-south. The valley bottom is occupied by Okanagan, Kalamalka, Skaha, Osyosoos and other minor lakes. Osoyoos Lake is the lowest point in the study area, at approximately 277 m asl. The Cascade Mountains contain the highest peaks in the study area. Grimface Mountain (2635 m asl) and its surrounding massif and Snowy Mountain (2589 m asl) are located in the Cathedral and Snowy Protected Areas, respectively. Major population centres are typically located on the peripheries of these lakes and the plains, terraces, and fans of major river valleys.

The Cordilleran Ice Sheet covered the entire study area during the most recent, Late Pleistocene Fraser Glaciation. Landforms and surficial sediment distribution are primarily a result of glacial modification. Ice generally flowed south, widening and steepening valleys while infilling them with drift. The high plateau surfaces that surround the lake and river valleys have rounded peaks that were eroded by the ice. As the glaciers retreated, many valleys were blocked by ice, impounding drainage, and forming glacial lakes. Thick accumulations of glaciolacustrine sediments were deposited on the bottoms of the lakes. Many of these deposits were later dissected by Late Pleistocene deglacial meltwater and early Holocene rivers, leaving terraces along the margins of the old glacial lake beds. Where meltwater was free-flowing, gravelly glaciofluvial terraces and plains formed at the margins and in front of the ice sheets. Major valleys typically have steep bedrock walls partially covered by thin veneers of colluvium or glacial drift where slopes are gentler. Colluvial fans and aprons are commonly present where steep gullies and unstable slopes meet the valley bottom. Large alluvial fans occur at valley junctions.

The glacial and deglacial landforms were particularly unstable until colonized by vegetation. Most of these landforms stabilized during the early Holocene paraglacial period (Church and Ryder, 1972), when erosion rates were orders of magnitude higher. Many large, paraglacial alluvial fans are no longer active, except for channels incised in their surfaces. Much of the deep gullying of drift-mantled mountainsides underlain by weak bedrock occurred during this period. These gullies, once established, are more likely to produce debris flows than adjacent open slopes as the continued down-cutting over-steepens their headwalls and sidewalls, and concentrates even more surface runoff (Millard, 1999).

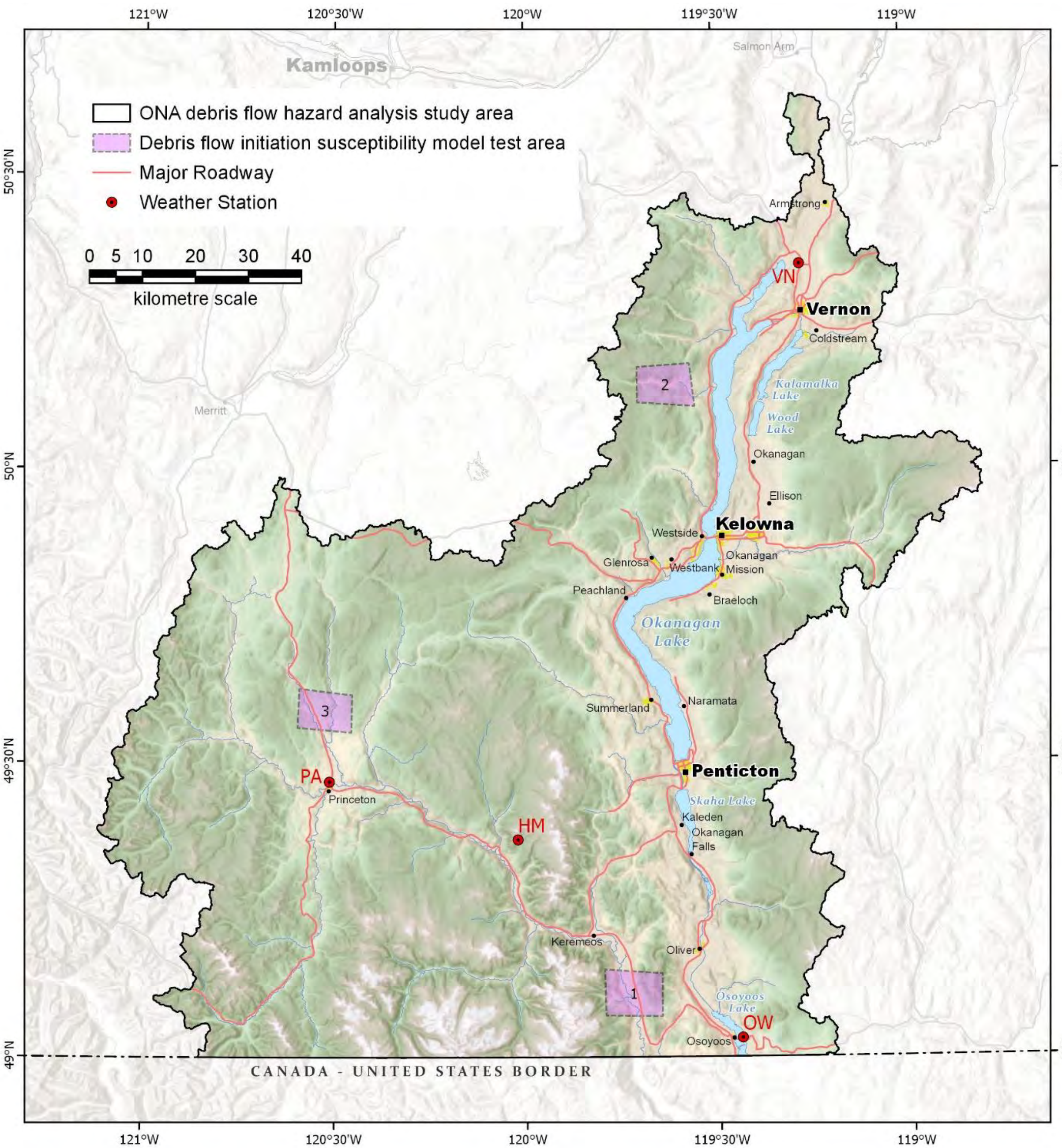

***Figure 1.1** ONA debris flow hazard analysis study area. Locations of weather stations (PA – Princeton A, HM – Hedley Mine, OW – Osoyoos West, VN – Vernon North) shown in Figure 1.2. Debris flow initiation susceptibility model test areas were used to map debris flow initiation sites shown in Figures 3.1, 3.2, and 3.3.*

1.2.2 Climate

Climate varies widely across the large study area. Much of the region is considered semi-arid, with less than 400 mm of annual precipitation falling at most of the major population centres (Figure 1.2)

(Environment Canada, 2019). However, mountain ranges and plateau areas can receive more than double this amount. Precipitation is bimodally distributed, with peaks in May-June and November-January. Freshet (spring melt) typically occurs between late April and mid June. Annual temperatures range from an average July daily high of 30°C in Osoyoos, to an average January daily low of 9°C in Princeton.

The mean annual temperature in the Okanagan Basin is expected to rise by 1.9° C by 2050 in association with climate change (Pacific Climate Impacts Consortium, Plan2Adapt). Annual precipitation is also estimated to increase by 6% over the same period, with a change in its seasonal distribution. Summers are predicted to have a 13% reduction in precipitation while winters are predicted to receive 6% more precipitation, albeit increasingly more as rain rather than snow. Winters are projected to receive 14% less snow, while spring snowfall is expected to decrease by more than 50%. These changes in temperature and the timing and intensity of precipitation are likely to produce an earlier freshet and an extended dry season.

1.3 Objectives

The objectives of this study were to:

- Produce an overview-level, desktop-based debris flow initiation susceptibility model for the Okanagan Basin.
- Validate the model using available landslide datasets and manual mapping of debris flow initiation zones.
- Model generalized debris flow paths using the initiation susceptibility model results to determine initiation zones and topographic data to delineate potential flow paths.

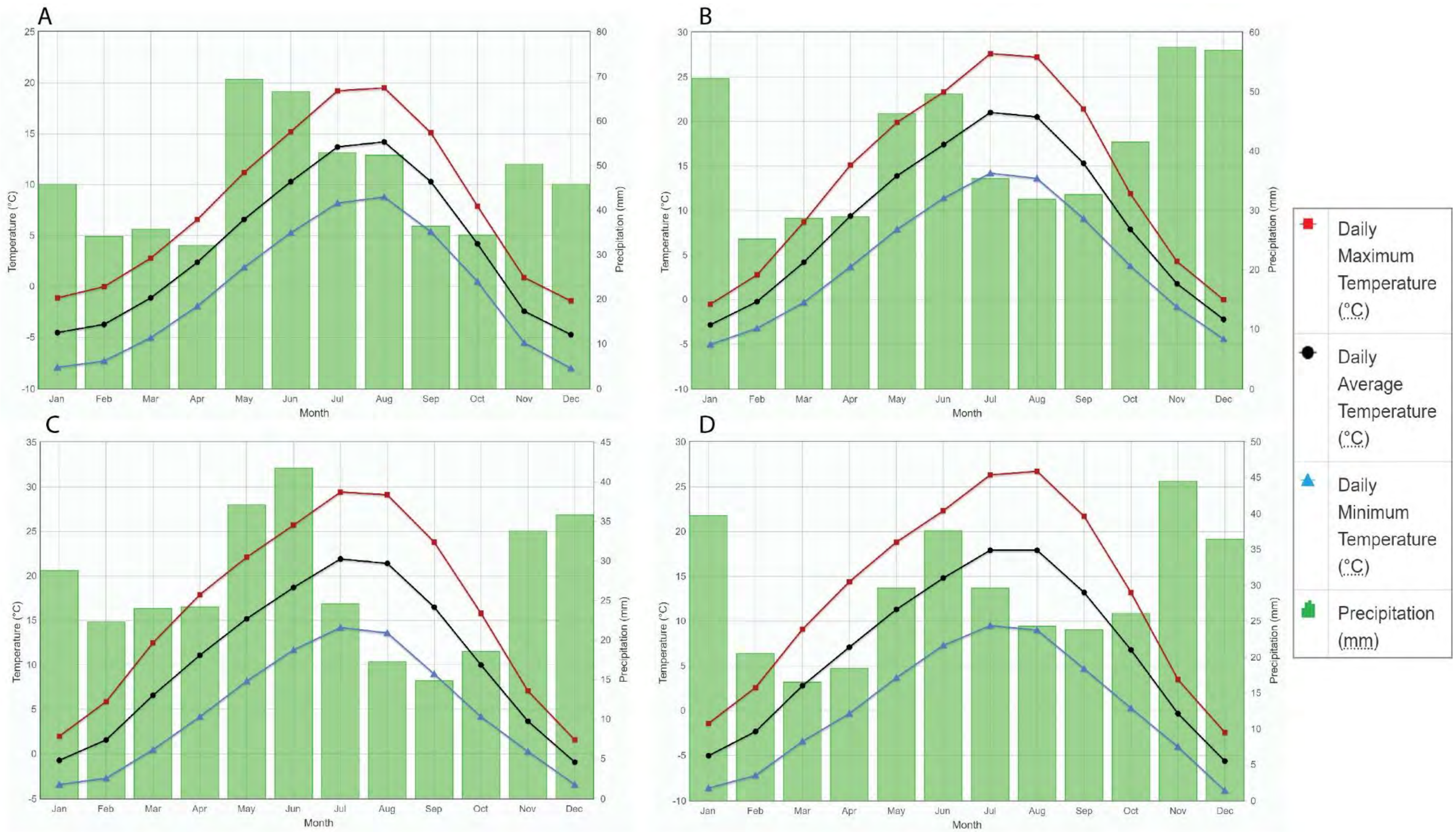

Figure 1.2 Canadian Climate Normals 1981-2010 for: A. Headley NP Mine weather station 49°22'10" N 120°01'18" W B. Vernon North weather station 50°20'39" N 119°16'17" W, 538.0 m asl. C. Osoyoos West weather station 49°01'55" N 119°26'34" W 297.2 m D. Princeton A weather station 49°28'04" N 120°30'45" W, 701.7 m asl. Weather station locations are shown in Figure 1.1. Environment Canada, 2019

2. Methods

2.1 Overview

Debris flow hazard in the Okanagan basin was assessed at a basin-wide, overview level, through a systematic, multi-step process. Desktop modelling was used to generate a spatially contiguous evaluation of debris flow initiation susceptibility across the landscape through the evaluation of existing datasets. Select test areas (Figure 1.1) were examined independently based on interpretation of aerial photographs. Visible debris flow initiation zones were mapped manually to create a local debris flow inventory. The results of the inventory were used to validate the debris flow initiation susceptibility model. Generalized debris flow path modelling was completed to extend area of high and very high initiation susceptibility down slope to identify areas potentially affected by debris flows. The model output classifies the study area by debris flow initiation susceptibility and highlights potential debris flow paths for use by Ebbwater to conduct its risk assessment.

2.2 Debris Flow Initiation Susceptibility Modelling

A qualitative heuristic approach was used to model debris flow hazard throughout the 15,500 km^2 study area. The debris flow hazard model is based on related landslide susceptibility mapping studies, including Dai and Lee (2001), Blais-Stevens *et al.* (2012), and Blais-Stevens and Behnia (2016). In these studies, the authors produce qualitative models identifying debris flow hazard initiation zones within large study areas in British Columbia and Yukon, which match well with pre-existing inventories of debris flow occurrence.

Our qualitative heuristic model was developed for the Okanagan Basin to identify terrain susceptible to debris flow initiation. We accomplished this through the selection of predictive terrain parameters associated with debris flow initiation based on previous studies (Dai and Lee 2001, Blais-Stevens *et al.* 2012, and Blais-Stevens and Behnia 2016). The parameters chosen are considered static, constant over time for a given location, and relate to the underlying cause of debris flows. Dynamic variables such as hydrological events, wildfire, and modification from logging are triggers acknowledged to locally increase the debris flow hazard; however, including these variables may lead to a model that becomes less representative as dynamic conditions change over short (hours to years) periods of time.

Each parameter is represented by a GIS-based data layer sorted into classes of low, moderate or high (Table 2.1). The classes are assigned values according to professional judgement and previous studies (Dai and Lee 2001, Blais-Stevens *et al.* 2012, and Blais-Stevens and Behnia 2016), and normalized between 0 and 1. The parameters are then weighted and combined in a GIS-based algorithm modified from Blais-Stevens *et al.* (2012) (Figure 2.1). The resulting output is a continuous surface representing debris flow initiation susceptibility, determined on a cell-by-cell basis with assigned values between 0 and 1, where 1 indicates comparatively higher susceptibility to debris flow initiation. The values were categorized using natural breaks into five classes: very low, low, moderate, high, and very high.

Slope gradient was estimated to be the most important predictor of debris flow initiation broadly across the study area due to increasing gravity-induced shear stress with gradient (Dai and Lee, 2001) and observed constraint of initiation zones to areas with relatively steep slopes. Slope classes were based on standardized breaks presented in the Terrain Classification System for British Columbia (Howes and Kenk, 1997). Surficial materials were classified according to their genetic origin and assumed to be of secondary importance to slope gradient. Surficial materials were weighted in accordance with their geotechnical properties. All else being equal, finer grained materials are considered more susceptible to landsliding than coarse grained materials due to their higher propensity to retain moisture and develop pore water pressures that reduce shear strength. Distance to drainage, the distance between a given point and the nearest water course, was used in this study and in previous studies (Blais-Stevens *et al.* 2012; Blais-Stevens and Behnia 2016) due to the tendency of debris flows to initiate in and travel down steep creeks and gullies (Millard, 1999). Bedrock geology was considered to play a variable role in the initiation of debris flow based on differences in the competence of various lithologies, although it was estimated to be of lesser importance than the other three predictors. Bedrock hazard ratings were assigned by comparison to relative values used by Blais-Stevens *et al.* (2012) and judgement of typical susceptibility to and style of weathering and lithological competence. Numerous other factors contribute to bedrock stability that are not addressed in this study, (e.g. structure) and considerable variation may exist within the input mapping. Follow-up studies are recommended to validate bedrock hazard values.

The GIS-based algorithm is:

$$\boldsymbol{Debris\ Flow\ Susceptibility} = (\mathbf{0.4} * \boldsymbol{Slope\ Gradient}) + (\mathbf{0.3} * \boldsymbol{Surficial\ Material}) + (\mathbf{0.2} * \boldsymbol{Distance\ to\ Drainage}) + (\mathbf{0.1} * \boldsymbol{Bedrock\ Geology})$$

The data used in this analysis were compiled and processed using ESRI’s ArcMap (version 10.6.1). Topography in the Okanagan Basin was represented using a Canadian Digital Elevation Model (CDEM) provided at a resolution of 20 m in the study area (Natural Resources Canada, 2016). Data layers were derived from this data source or compiled from publicly available sources and resampled to a raster grid at the CDEM resolution (20 m). Surficial materials were compiled from a mosaic of terrain and terrestrial ecosystem mapping datasets obtained from the DataBC catalogue. Bedrock geology was represented using British Columbia digital geology (Cui, Miller, Schiarizza, & Diakow, 2017). Distance to drainage was calculated using the stream network provided by the BC Freshwater Atlas.

Table 2.1 Debris flow initiation susceptibility parameters and hazard values. Overlay analysis of weighted susceptibility parameters is shown in Figure 2.1

Slope Gradient (°)	**Class (L, M, H)**	**Hazard Value (0.0 – 1.0)**
Plain (0 – 3°)	L	0.0
Gentle (4 – 15°)	L-M	0.25
Moderate (16 – 26°)	M	0.5
Moderately Steep (27 – 35°)	M-H	0.75
Steep (>35°)	H	1.0
Surficial Material	**Hazard Class (L, M, H)**	**Hazard Value (0.2 – 1.0)**
Anthropogenic	L	0.2
Fluvial, Glaciofluvial	L	0.2
Eolian	L-M	0.4
Morainal	M	0.5
Organic	M	0.6
Bedrock	M	0.6
Weathered Bedrock/Saprolite	M-H	0.8
Volcanic and Undifferentiated Material	M-H	0.8
Colluvium	H	1.0
Lacustrine, Glaciolacustrine	H	1.0
Distance to Drainage	**Hazard Class (L, M, H)**	**Hazard Value (0.25 – 1.0)**
>150 m	L	0.25
100 – 150 m	L-M	0.5
50 – 100 m	M-H	0.75
0 – 50 m	H	1.0
Bedrock Geology	**Hazard Class (L, M, H)**	**Hazard Value (0.25 – 1.0)**
Metamorphic (orthogneiss, paragneiss)	L	0.25
Intrusive (dioritic, granitic, granodioritic, tonalite, syenitic to monzonitic, undivided)	L	0.25
Sedimentary (Chert, siliclastic)	L	0.25
Ultramafic	L	0.25
Metamorphic (greenstone, greenschist, lower amphibolite/kyanite grade, undivided)	M	0.5
Sedimentary (coarse clastic, undivided)	M	0.5
Volcanic (alkaline, calc-alkaline, undivided)	M-H	0.75
Sedimentary (marine, mudstone, siltstone, shale fine clastic, siliceous argillite)	H	1.0
Volcanic (rhyolite, felsic, volcaniclastic)	H	1.0

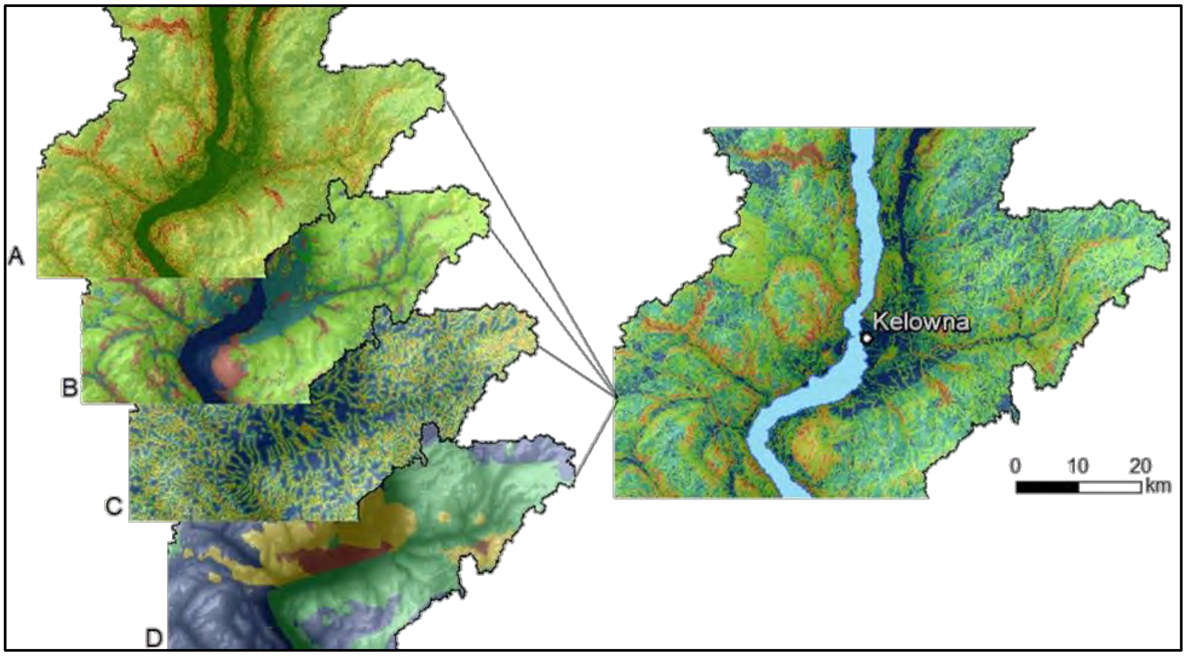

Figure 2.1 Debris flow initiation susceptibility model inputs (left): A. Slope gradient B. Surficial material C. Distance to drainage D. Bedrock geology. These inputs are combined to create the debris flow initiation susceptibility model (right).

2.2.1 Manual Mapping and Validation

The debris flow initiation susceptibility model was checked for accuracy by completing manual mapping of debris flow initiation zones in three test areas (Figure 3.1, Figure 3.2, and Figure 3.3) distributed throughout the study area (Figure 1.1). Each sample area was selected to contain a broad range of terrain and hazard classes representative of the larger study area, with an emphasis on areas containing steep and gullied terrain. Manual mapping relied upon interpretation of aerial photography in a 3D visualization software, DAT/EM Summit. Aerial photographs were collected in 2001 for sites 1 and 2, and 2003 for site 3. All aerial photographs were 1:30,000 scale. The initiation zones were compared to the model hazard rating with the expectation that the number of initiation zones would increase exponentially with an increase in hazard rating.

A second validation of the results of our model was performed using a landslide inventory provided by Westrek Geotechnical Services Ltd. This inventory is located approximately between Sicamous and Revelstoke, British Columbia, over an area encompassing the Trans-Canada Highway. These landslide events are found between 15 and 70 km northeast of the Okanagan Basin study area. Debris flow initiation susceptibility modelling was extended to cover a 1,000 km^2 area containing the landslide inventory (Westrek landslide study area). At the resolution of the inventory, all landslides involving mass movement of debris (e.g. debris flows, debris slides, debris floods) were considered relevant for validation purposes. A total of 163 landslide events was identified that meet these criteria. Sixty-six percent of inventoried landslides occurred in areas classified as high susceptibility or greater, and 93% of landslide events occurred in terrain classified as moderate susceptibility or higher.

The landslide events were then normalized to the total area of each hazard class within the Westrek landslide study area. The highest densities of debris-type landslide events occurred within the very high and high susceptibility classes.

2.3 Generalized Debris Flow Path Modelling

Generalized debris flow path modelling was completed in order to extend areas of high and very high debris flow initiation susceptibility downslope as a rough approximation of runout potential. Model results are included in Appendix A. This model was developed utilizing SAGA GIS's terrain analysis tool "flow path length" to identify flow paths downslope of terrain classified as high and very high susceptibility by the debris flow initiation susceptibility model. Flow paths descending slopes gentler than 4°, the minimum recorded angle of debris flow fans in British Columbia (VanDine, 1996), were clipped (removed) from the final model output. Finally, the model was adjusted to remove portions of apparent flow paths extending more than 2 km from the nearest cell of high or very high debris flow initiation susceptibility. This step was necessary to remove considerable overestimates of debris flow paths in broad valley bottoms and on continuously gentle slopes. It is possible for debris flows to travel beyond 2 km from their source areas; however, because most channelized debris flow paths are likely already be classified as areas with high or very high initiation susceptibility, it is unlikely that this process removed many debris flow channels. The final generalized debris flow path model effectively extends debris flow hazard downslope from high and very high debris flow initiation susceptibility terrain until topography limits its travel. The generalized debris flow paths were not classified with the same high and very high hazard categories to avoid misrepresenting model precision; however, they likely represent a level of hazard ranging from very high to moderate depending on the hazard category, cumulative area, and proximity of upslope initiation zones. The model uses the 20 m CDEM as its surface and is subject to the limitations of that dataset, including its scale, accuracy, and precision.

3. Results

3.1 Debris Flow Initiation Susceptibility

The results of the debris flow initiation susceptibility modelling are presented in Appendix A. The distribution of debris flow initiation susceptibility is summarized in Table 3.1. Very low initiation susceptibility terrain consists of generally level ground such as floodplains and terrace treads, without incised creeks or gullies. All surficial material types may be present. Debris flows are unlikely to initiate in very low initiation susceptibility terrain. Low initiation susceptibility terrain consists of gently sloping terrain, rarely adjacent to creeks or gullies or moderate to moderately steep terrain away from drainage features and containing more stable surficial materials. Debris flows are unlikely to initiate in low initiation susceptibility terrain. Moderate initiation susceptibility terrain varies from moderate gradients with less stable surficial materials to moderately steep with relatively stable surficial materials; this terrain may be in close proximity to creeks and gullies. Debris flow initiation is rare in moderate initiation susceptibility terrain. High and very high initiation susceptibility terrain is typically found on the steepest slopes and along or adjacent to steep creeks and gullies. Less stable surficial materials (e.g. glaciolacustrine) may result in high or very high initiation susceptibility terrain on moderate or moderately steep slopes, particularly those near creeks and gullies. Debris flow and other landslide scars are common in very high initiation susceptibility terrain.

Table 3.1. Debris flow initiation susceptibility class distribution and area affected by generalized debris flow paths.

Debris Flow Initiation Susceptibility Class (Model Value)	Total area (km^2)	% of Study Area	Observed Landslide Density (events/km^2)
Very Low (0.0-0.27)	1428	9.3	0
Low (0.27-0.40)	5492	35.5	0
Moderate (0.40-0.53)	4626	30.0	0.4
High (0.53-0.70)	2669	17.3	1.8
Very High (0.70-1.0)	1219	7.9	4.8
Generalized Debris Flow Paths	908	5.9	-

3.2 Model Validation

Manual mapping of the test areas (Figures 3.1, 3.2, and 3.3) found that the debris flow model effectively classified debris flow initiation susceptibility throughout the study area. One hundred eighty-eight debris flow initiation points were mapped across the three test areas. Figures 3.1, 3.2, and 3.3 show the distribution of debris flow initiation points within the test sites. Validation by manual mapping was generally comparable to the validation using Westrek's landslide database (Figure 3.6). The discrepancy between the two validation methods is likely due in part to the inclusion of additional types of debris-type landslides, and uncertainty in the exact location of initiation zones in the inventory. The manual debris flow inventory is the preferred validation method for this study; however, the Westrek database validation supports the model's capability in capturing most landslides within high and very high susceptibility classes.

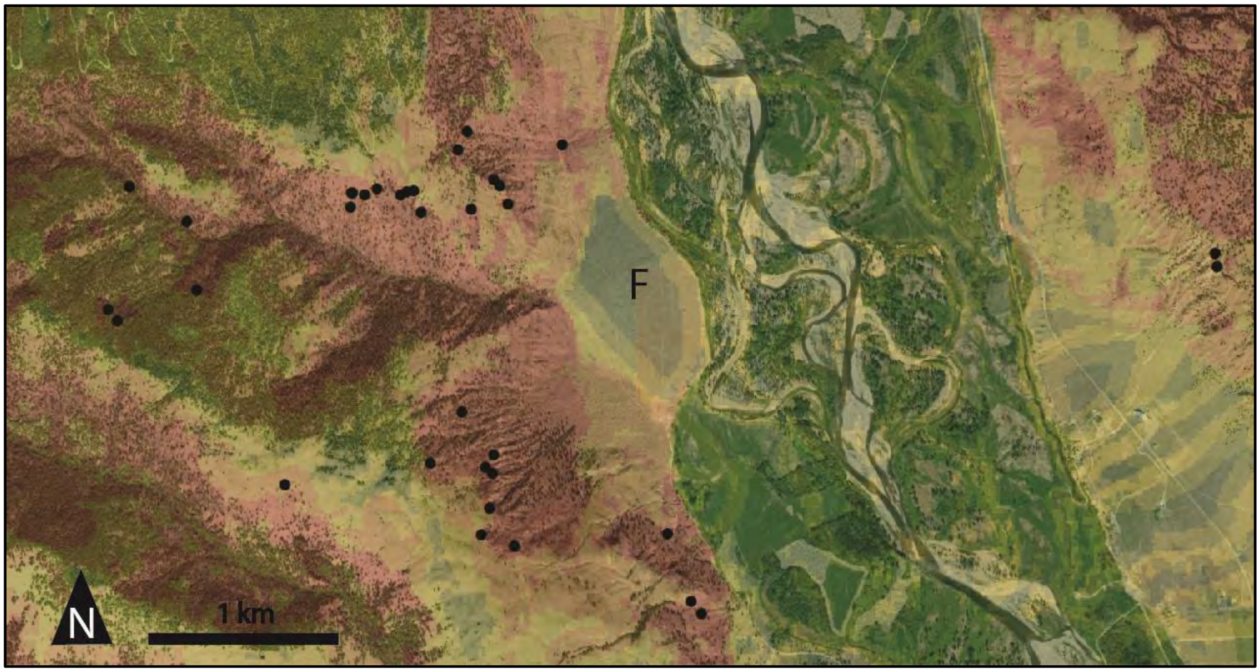

Figure 3.1 Manually delineated debris flow initiation zones (points) overlain on the debris flow hazard model at test area 1, 11 km south of Keremeos, British Columbia. All initiation zones are located in terrain classified as high (orange) or very high (red). Of note is the large fan in the centre of the photo (F), which is likely affected by debris flows. This fan is mostly classified as very low or low initiation susceptibility but is effectively captured by generalized debris flow path modelling. The test area location is shown in Figure 1.1

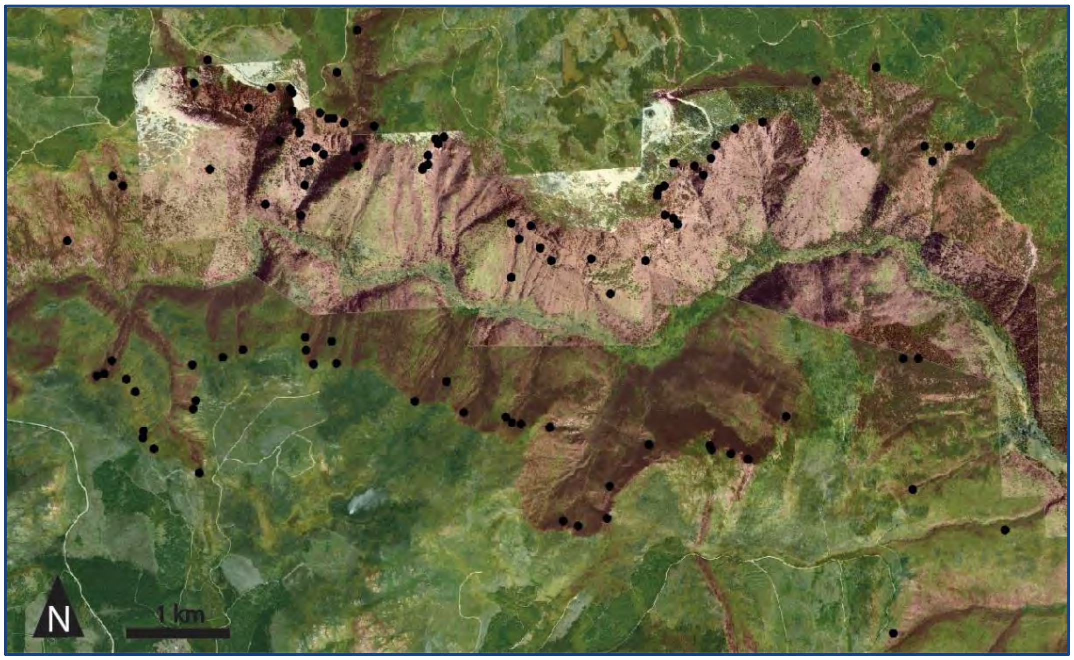

Figure 3.2 Manually delineated debris flow initiation zones (points) overlain on the debris flow hazard model at test area 2 within Fintry Provincial Park, British Columbia. The test area location is shown in Figure 1.1.

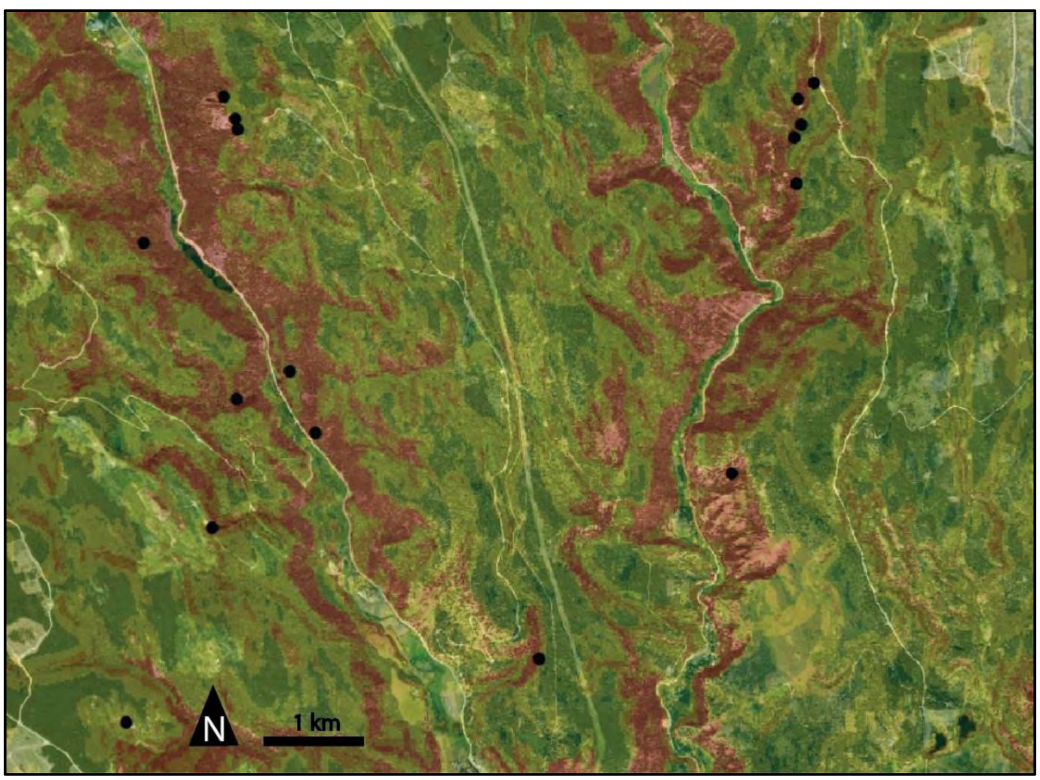

Figure 3.3 Manually delineated debris flow initiation zones (points) overlain on the debris flow hazard model at test site 3, 15 km north of Princeton, British Columbia. The test area location is shown in Figure 1.1.

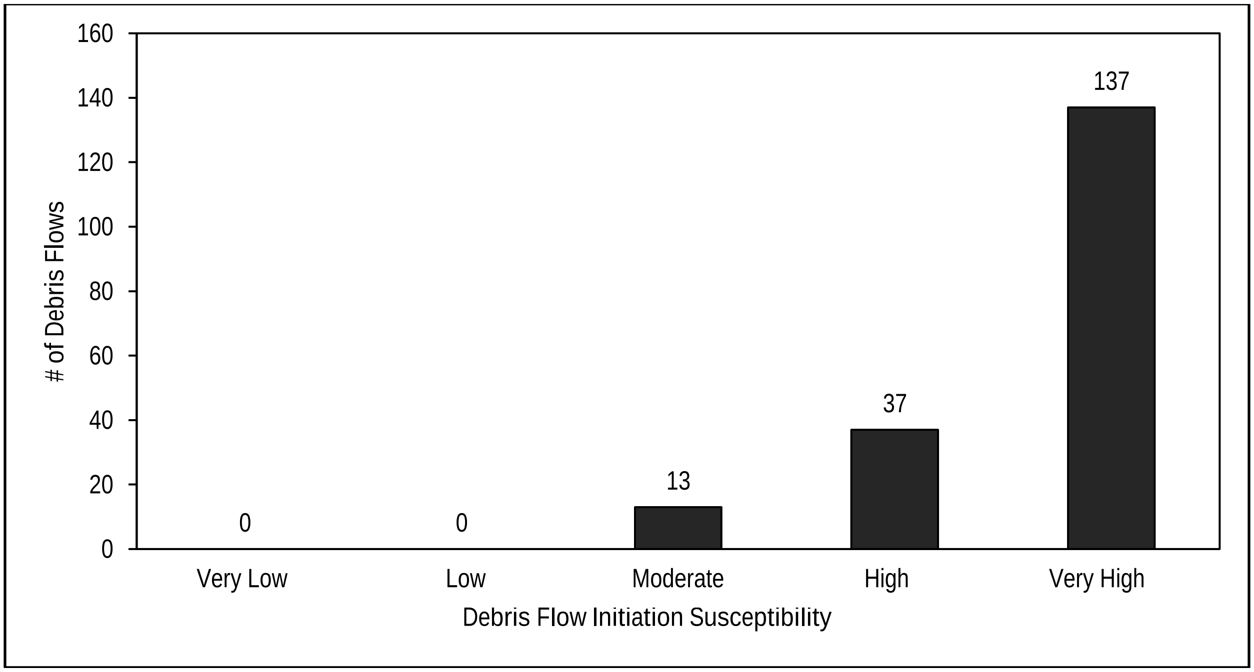

Figure 3.4 Number of debris flows inventoried in each debris flow initiation susceptibility class.

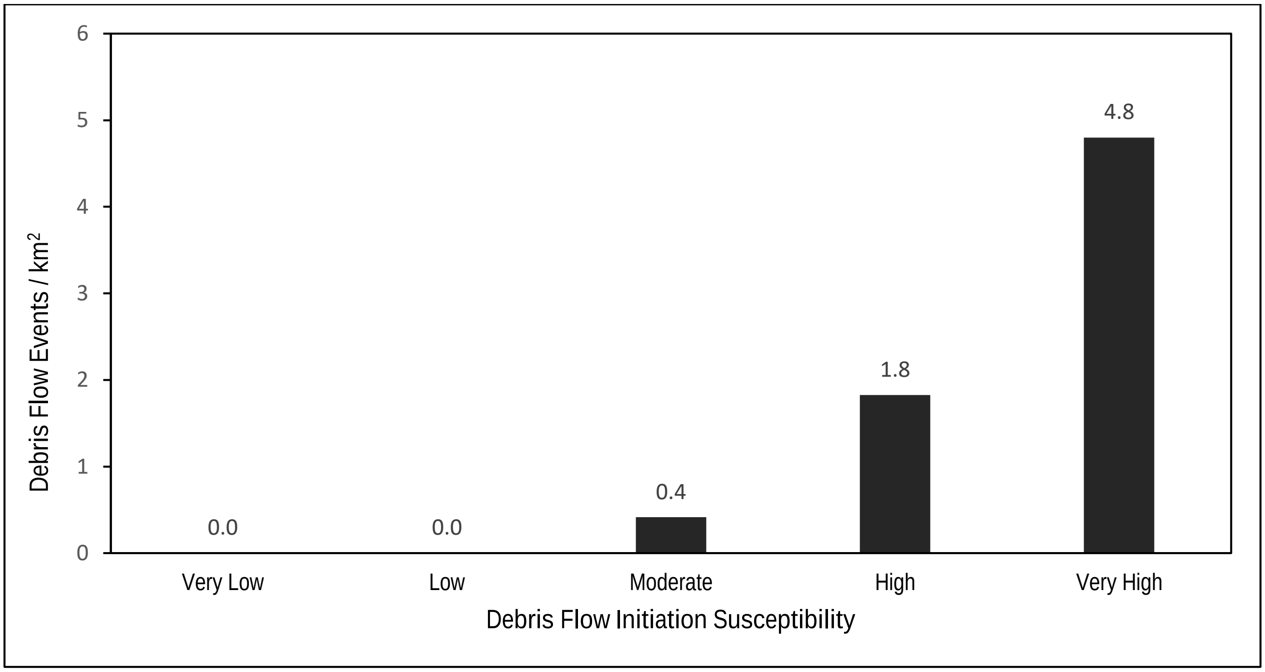

Figure 3.5 Debris flow areal density versus debris flow initiation susceptibility classification based on aerial photograph inventory at the three test locations.

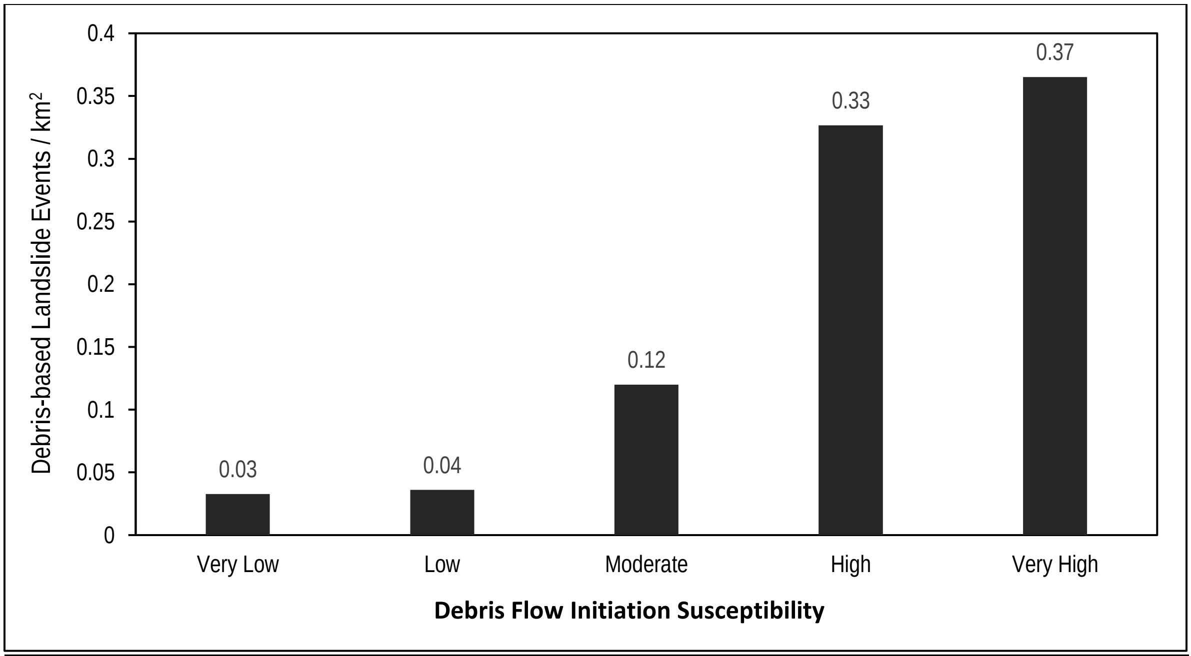

Figure 3.6 Debris-type landslide density versus debris flow initiation susceptibility classes between Sicamous and Revelstoke, British Columbia. Note that this data set also contains other debris landslide types including debris slides, debris avalanches, debris slumps, and debris floods.

3.3 Generalized Debris Flow Paths

The results of the generalized debris flow path modelling are presented in Appendix A. The total affected area is summarized in Table 3.1. Figure 3.7 shows an example of this output overlain on the debris flow initiation susceptibility model. The fan identified in Figure 3.1 is shown in Figure 3.7 as an area overlain by the generalized debris flow paths. The model output effectively extends high and very high hazard terrain from the debris flow initiation susceptibility model downslope to its maximum theoretical extent in much of the study area. The relative hazard rating of these runout paths is difficult to determine but is likely similar to the high to very high rating of its initiation zones. Misclassifications in the model output are typically caused by errors or inaccuracies in the CDEM. The generalized debris flow paths have not been ground-truthed or validated beyond cursory review and are best interpreted as a rough approximation of debris flow runout potential for use in identifying areas for further analysis.

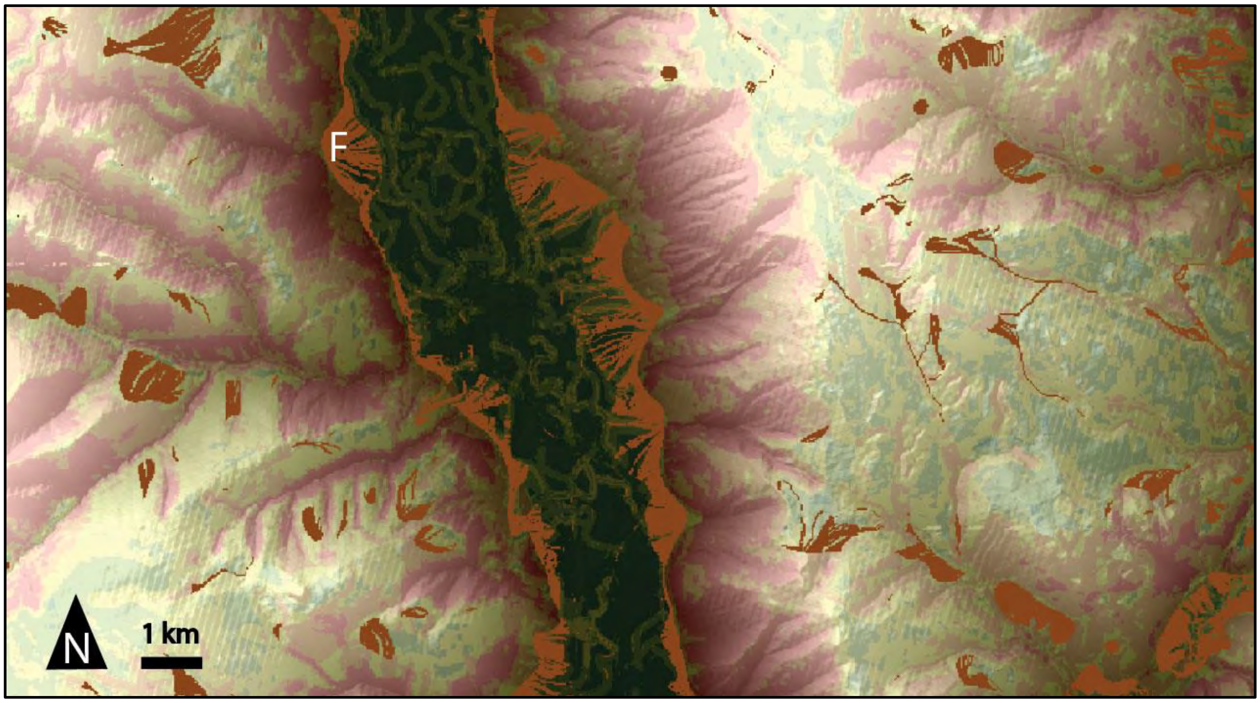

Figure 3.7 Generalized debris flow paths (brown) overlain on debris flow hazard model (green through red). This image encompasses test site 1. Debris flow fans and aprons are identifiable along the valley walls below high and very high hazard terrain. The fan marked "F" is also shown in Figure 3.1. Rare elongate channelized debris flow paths on the plateau surface on the east side of the figure are likely over-estimates of actual path lengths due to long, relatively gentle slopes that exceed the model's 4° threshold. Debris flow paths are not calculated within high and very high hazard terrain and may appear truncated as a result.

4. Additional Considerations

4.1 Model Limitations

The debris flow hazard modelling was completed at a basin-wide scale to identify areas prone to debris flows. The goal of this study is to highlight areas with concentrations of debris flow initiation susceptibility or activity to inform Ebbwater's risk assessment.

The following limitations should be considered when interpreting these results:

- The debris flow initiation susceptibility model is intended to highlight areas susceptible to debris flow initiation. Its output does not consider or represent debris flow transport (conveyance) or runout. Debris flows may travel downslope into regions identified as comparatively low initiation susceptibility. The outputs accounts for debris flow transport using generalized debris flow paths as a proxy; however, this model has not been validated beyond cursory review.

- Terrain parameters were chosen at scales that were practical and available across the entire Okanagan Basin. Higher resolution data may be available locally (e.g. LiDAR imagery) but were not incorporated into this model.
- Dynamic external (non-terrain) parameters such as climate change, forest fire, groundwater conditions, storm event, and logging have the potential to increase the likelihood of debris flow initiation, locally, but have not been included in the model due to their temporal variability. Future work may include effects of these parameters to give a more comprehensive understanding of debris flow hazard.
- Susceptibility classes were defined using natural breaks, which has the advantage of minimizing within-group variability and maximizing between-group variability. However, classes may not directly translate to the expected magnitude and/or frequency of events.

4.2 Effects of Dynamic Parameters

Dynamic parameters, external to terrain, were not included in the modelling, although their general impacts on debris flow occurrence in the study area warrant acknowledgment.

4.2.1 Storms and Precipitation

Climate change can affect landslide activity in several ways. Increased amounts or intensities of precipitation, stronger seasonality, and changes in snowpack and snowmelt can influence landslide frequency, magnitude and distribution. Warmer year-round temperatures can also affect landslide activity through changes to the hydrogeomorphic balance of a region. High-intensity rainfall events, rain on snow and prolonged periods of high precipitation result in a higher frequency of landslides (Jakob and Lambert, 2009), particularly in areas with a functionally unlimited sediment supply. The study area contains regions of supply-limited and supply-unlimited watersheds, which respond differently to increased precipitation and frequency of storms (Bovis and Jakob, 1999). Areas that are supply-limited may not experience an increase in debris flow frequency or magnitude; however, supply-unlimited watersheds may be significantly affected. In coastal British Columbia, landslide frequency could increase up to 28% due to changing precipitation regimes and increasing storm frequency; however, the variation in landslide volumes will be dependant on sediment supply within each catchment (Jakob and Lambert, 2009). Due to hot summer temperatures in the Okanagan, strong localized convective storms may also temporarily increase debris flow hazard (Tannant and Skermer, 2013).

4.2.2 Wildfire

Wildfires are relatively common in the Okanagan Basin. A number of debris flows, debris floods, and debris slides were triggered by rainstorms following the 2003 extreme fire season in the southern Okanagan (Jordan and Covert 2009). Climate change may increase the frequency and severity of wildfires due to a longer dry season with more frequent lightning strikes associated with convective storms, leading to a greater occurrence of landslides due to:

- The removal of vegetative ground cover and the forest canopy, which intercepts rainfall, enhances evapotranspiration, and stabilizes soils.

- The presence of hydrophobic soils on slopes burned with a moderate to high severity. This can increase surface runoff and cause significant erosion, increasing the likelihood of debris flows or debris floods.

These projections are supported by Hope et al. (2015), who noted that the frequency of landslides in a given area is likely to increase following wildfire, though they will primarily occur in the same terrain as in pre-wildfire conditions. It is expected that the elevated post-wildfire landslide hazard would subside once vegetation re-establishes to pre-burn conditions.

4.2.3 Seismicity

The Okanagan Basin is in a region of moderate seismic hazard. Seismicity has not been included as a parameter in the hazard model due to the inability to predict locations of seismic events (earthquakes) and magnitudes. Landslides can be triggered by earthquakes of sufficient magnitude and proximity. The relationship between magnitude, proximity and landslide type is shown in Figure 4.1. No historic earthquakes in or near the study area (Halchuck et al., 2015) are known to have triggered landslides.

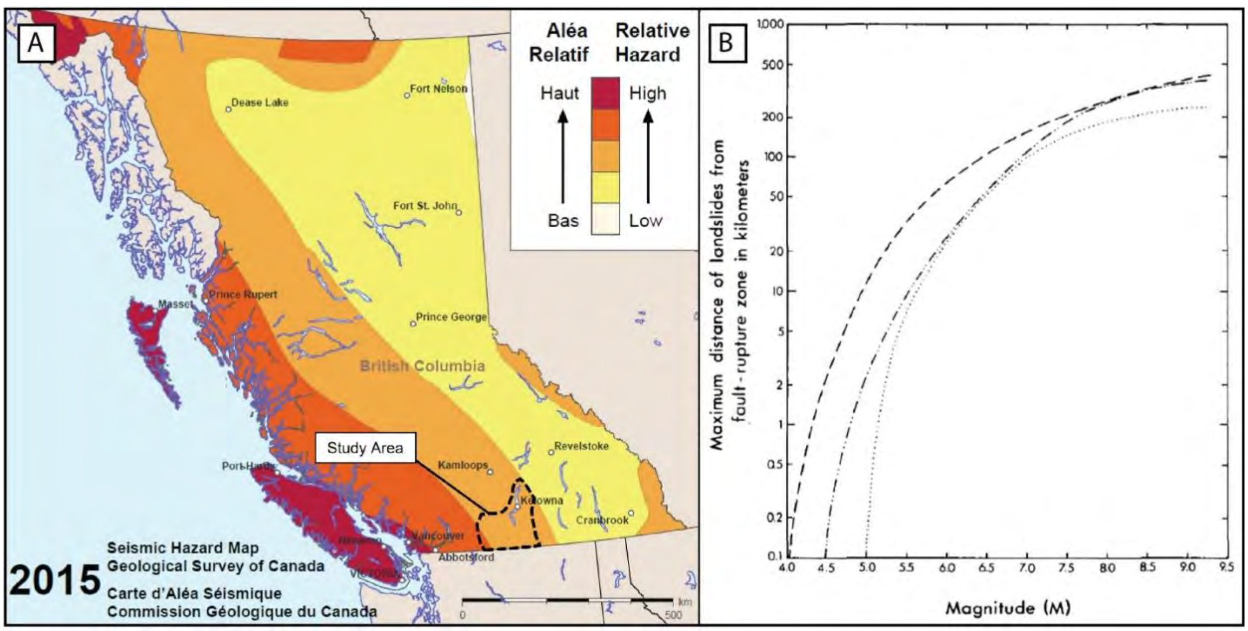

Figure 4.1 A. Generalized seismic hazard map for British Columbia (NRCAN, 2015) showing the approximate bounds of the study area. B. Relationship between earthquake magnitude and distance at which ground movement may trigger landslides, as determined by Keefer (1984). The dashed line represents disrupted falls and slides, the dashed-double-dotted line represents coherent slides, and the dotted line represents lateral spreads and flows, including debris flows.

5. Conclusion and Recommendations

5.1 Conclusions

A qualitative heuristic debris flow initiation susceptibility model was produced for the study area based on previous work by Dai and Lee (2001), Blais-Stevens et al. (2012), and Blais-Stevens and Behnia (2016) . The susceptibility model output was validated by manual mapping at three test sites and compared to a landslide database provided by Westrek. The model estimates the following breakdown of debris flow initiation susceptibility within the study area:

- 1219 km^2 of very high debris flow initiation susceptibility terrain
- 2669 km^2 of high debris flow initiation susceptibility terrain
- 4626 km^2 of moderate debris flow initiation susceptibility terrain
- 6920 km^2 of low or very low debris flow initiation susceptibility terrain

Generalized debris flow path modelling was completed to extend the areas affected by high and very high initiation susceptibility terrain downslope. The generalized debris flow path modelling identified an additional 908 km^2 of moderate or lower initiation susceptibility terrain potentially affected by debris flows initiating upslope in terrain with high or very high initiation susceptibility.

5.2 Recommendations for Further Work

This assessment represents an important step in understanding landslide hazards within the study area. The results underscore the need for follow-up work to address several important issues that relate to debris flow risk:

- Further validation of the debris flow initiation susceptibility and generalized debris flow path inputs and modelling outputs using a detailed multi-year debris flow inventory for the study area.

- A detailed analysis of debris flow hazard within areas identified with increased risk by Ebbwater's risk assessment, including quantitative magnitude/frequency analysis to determine if areas of high risk exceed acceptable thresholds or are likely to exceed acceptable thresholds in the future based on climate change projections.
- Incorporate hazard of dam breaches into debris flow models using existing dam inventories (BC MFLNRO, 2011), due to their historic association with debris flows in the Okanagan Basin (Tennant and Skermer, 2013).
- Hydrogeomorphic process classification (cf. Wilford et al. 2004) of high-risk watersheds to determine character of channelized debris-type mass movements (e.g. debris flow vs. debris flood) and how to best manage the hazard-type as it moves through the watershed.

6. Limitations

This report has been prepared by Palmer Environmental Consulting Group Inc. (PECG) for Ebbwater Consulting Inc. (Ebbwater), working on behalf of the Okanagan Nation Alliance (ONA), in accordance with the agreement between Consultant and Client, including the scope of work detailed therein (the “Agreement”). The report and the information it contains may be used and relied upon only by Client, except (1) as agreed to in writing by Consultant and Client, (2) as required by-law.

The extent of this study was limited to the specific scope of work for which we were retained and is described in this report. PECG has assumed that the information and data provided by the client or any secondary sources of information are factual and accurate. PECG accepts no responsibility for any deficiency, misstatement or inaccuracy contained in this report as a result of omissions, misinterpretations or negligent acts from relied-upon data. Judgment has been used by PECG in interpreting mass movement hazards based on desktop analyses; no technical site visits were undertaken. Use of this work should consider the scale of the modelling when determining its applicability to site-specific evaluations. This work is not a substitute for a Legislated Landslide Assessment (APEGBC, 2010).

PECG is not a guarantor of site conditions or projected characteristics of mass movements but warrants only that our work was undertaken, and our report prepared in a manner consistent with the level of skill and diligence normally exercised by competent geoscience professionals practicing in British Columbia. Our findings, conclusions and recommendations should be evaluated considering the limited scope of our work.

7. Certification

This report was prepared and reviewed by the undersigned:

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Geoscientist

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Appendix A

See files contained within PECG_ONA_Debris_Flow_Hazard.gdb