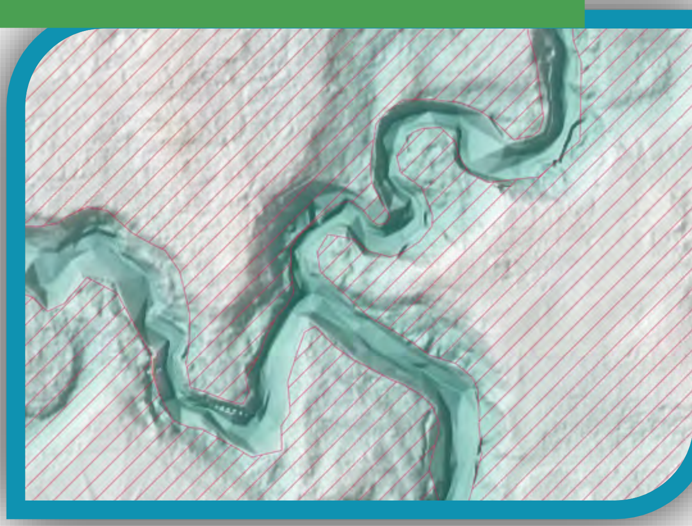
City of Dawson Creek Flood Mapping

Final Report



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Cover Photo: Merged LiDAR and bathymetric data for hydraulic modelling.
Ebbwater Consulting Inc. image.

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2	15 April 2020	Tamsin Lyle, P.Eng.	Final Report	*Original signed by Tamsin Lyle*
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The authors wish to acknowledge the support of the City of Dawson Creek project manager, Chelsea Mottishaw (Watershed Coordinator), Kayla Giovannini (Watershed Technician), and other City staff who supported this project. We would also like to thank the staff at the BC National Hydrological Services, Environment and Climate Change Canada, for providing hydrometric Water Survey of Canada data, and the Pacific Climate Impacts Consortium for sharing their hydrological modelling output with us.

We would like to acknowledge that this report was written at the Ebbwater Consulting Inc. (Ebbwater) office, which is located on the unceded and Traditional Territory of the Coast Salish Peoples.

The analysis was completed and the report written by a multi-disciplinary team led by Ebbwater as follows:

- Silja Hund, Ph.D., completed the hydrology analysis.
- Nikoletta Stamatatou, M.S., M.Eng., EIT, and Jessica Cochrane, M.S., TX EIT (US), completed the hydraulic modelling and flood mapping with senior oversight.
- Dickon Wells, M.Eng., completed the stormwater drainage assessment and channel conditions survey.
- Robert Larson, M.Sc., A.Ag., managed the project and overall report writing.
- Tara Sherman, P.Eng., provided guidance for the stormwater drainage assessment.
- Tamsin Lyle, M.Eng., MRM, P.Eng. (Principal of Ebbwater) was the project technical lead and provided final review of the report.

Ebbwater's subcontractors completed the following tasks:

- Vector Geomatics Land Surveying Ltd.: Bathymetric survey and digital elevation model (DEM) merging.
- Palmer: Fluvial geomorphology assessment.
- Adrian Chantler, Ph.D., P.Eng.: Senior technical review of flood maps and report.
- Sarah MacKinnon (Interwoven Editing): Copy-editing services.

Executive Summary

The community of City of Dawson Creek (City) has felt the impacts of flood hazard in recent years. When infrastructure was disrupted in 2016, people and businesses were greatly affected. In response, the City and other levels of government have made a significant effort to manage flood impacts by spending millions of dollars on crossing upgrades, and hundreds of thousands on emergency response in the last few years alone. A larger strategic planning effort to reduce flood risk over time was impeded by the lack of a modern up-to-date flood map, the foundational tool for flood management.

The goal of the current project is to provide flood mapping for the City that meets regulatory standards and guidelines, to support future planning and infrastructure decisions. To complement the flood mapping, a fluvial geomorphological assessment identifies secondary hazard zones such as erosion. Similarly, a stormwater drainage assessment identifies priority outfalls potentially affected by riverine flood and linked to backflow hazard. These assessments are meaningful for land use and building policy, as well as water management planning.

Ebbwater Consulting Inc. and its partners Palmer and Vector Geomatics Land Surveying Ltd. conducted this multi-disciplinary study that included topographic surface development, hydrologic analysis, hydraulic modelling, flood hazard mapping, fluvial geomorphological assessment and hazard mapping, and stormwater drainage assessment. A summary of the technical approaches is provided in Table 1 at the end of this executive summary.

To take advantage of the hydraulic model developed for flood mapping, a conceptual evaluation of structural mitigation options is provided. The evaluation takes a watershed perspective by considering fluvial geomorphological considerations.

Flood Mapping

Flood mapping was developed using best practice data and methods. The outputs also consider best practice and were developed specifically with consideration of their end use in planning and policy, and also to inform a future risk assessment. Therefore, in this study, 12 flood scenarios were considered. These included the 50%, 20%, 10%, 2%, 1%, and 0.5% Annual Exceedance Probability (AEP) floods (2-, 5-, 10-, 50-, 100-, and 200-year indicative return periods, respectively). These 6 AEPs were considered both under existing conditions and with climate change for the future period centred on 2050 (i.e., 2041-2070). Map tiles showing flood depths and extents for the above flood scenarios are provided in the accompanying Flood Hazard Map Atlas. In addition to these maps that show flood depths, the map atlas includes a map designed to meet the Provincial guidelines for the development and use of Flood Construction Levels (FCL) (a sample is shown in Figure 1). Further, hazard severity maps, which consider both flood depth and velocity, and provide a good proxy to understand the power of flood waters to damage structures or hurt humans, were also developed. Hazard severity maps provide information that can be used to inform emergency response and land use planning.

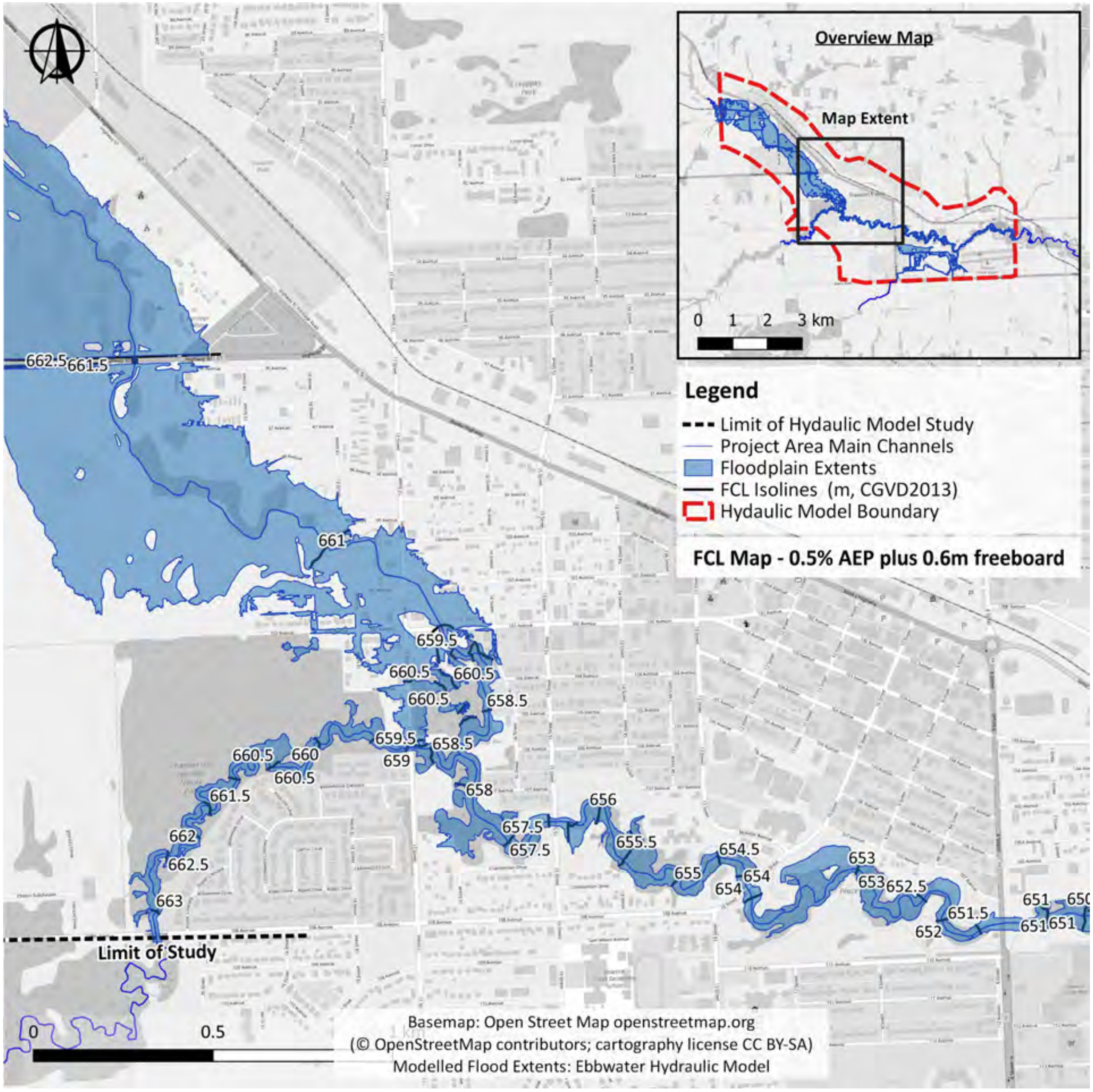

Figure 1: Flood Construction Level map for example area of the City of Dawson Creek.

Hydrologic Assessment

A hydrologic assessment was conducted to understand expected volumes of flow into the Dawson Creek system under various scenarios. These results were then used in the hydraulic model.

The assessment used local and regional hydrometric data (i.e., observed water levels and flows) to develop statistical models under existing and future expected conditions for Dawson Creek and its major tributaries. Under the existing conditions 0.5% AEP scenario (the standard regulatory event in BC), peak flows on the mainstem of Dawson Creek were estimated to be 67 m^3/s.

It was estimated that the 2016 flood event was equivalent to a storm with an annual exceedance probability (AEP) of approximately 1.3%. The standard design event (0.5% AEP) is 52% larger than what was observed in 2016.

With climate change, the analysis showed increases in flow volumes across all scenarios for the 2050s. This is a function of changing precipitation and temperature. Projected flows are greatest in mid-century, when snowpacks and high temperatures combine. For the 0.5% AEP scenario, projected peak flows on the mainstem of Dawson Creek are 83 m^3/s in the 2050s, an increase of 24% over existing conditions.

Hydraulic Modelling and Assessment

In order to understand how water moves across the floodplain under different flow scenarios a 2D hydraulic model was developed. The hydraulic model incorporated the estimated inflows, as well as surveyed bathymetric and LiDAR data to represent a 21 km length of the Dawson Creek Channel, as well as the South Dawson Creek and Ski Hill Creek tributaries, in high resolution. In total, 19 hydraulic structures, including major crossings such as at the Dangerous Goods Rt., 102nd Ave., 10th St., 15th St., and 8th St. formed the model geometry.

The model shows that for most scenarios flooding is primarily kept in-channel downstream of the confluence of Dawson Creek and South Dawson Creek. Upstream of the confluence, flooding spills overbank and inundates relatively large widths of land. This is to be expected given the channel morphology (shape), where in the lower reaches it is relatively steep and incised, and in the upper reaches has a shallower slope and a more gently sloping floodplain.

The extent of flooding, under existing conditions, for the very high magnitude flood (0.5% AEP, 200-year) is 3.1 km^2; the flood extent is 0.6 km^2 for the very low flood (50% AEP, 2-year). Under climate change, the flood flows and therefore flood extents are larger. The largest relative changes between now and the 2050s occurs for the lower magnitude floods (e.g., flood extents increase by as much as 25%, compared to existing conditions, for the low magnitude flood (20% AEP, 5-year)). This is an important finding as it highlights the need to plan and design for lower magnitude, but more frequent floods.

Geomorphologic Assessment

In addition to the hydraulic assessment, a complementary assessment was conducted to better understand past and future erosion potential on the Dawson Creek system. Erosion was highlighted as a secondary hazard in previous work. This fluvial geomorphological hazard assessment found that, since 1959, the Dawson Creek has undergone extensive anthropogenic realignment and straightening. Between 1959 and 2019, the Creek has decreased by approximately 31% (6 km) in channel length. The decrease has significantly reduced channel sinuosity and correspondingly increased channel slope. This pronounced shortening and steepening alters natural fluvial processes (e.g. sediment recruitment, planform progression, channel incision) and greatly influences flood conveyance and routing. The assessment's mapping identified 28 lateral erosion hazard zones and 27 potential avulsion sites. The geomorphologic hazard mapping complements the hydraulic hazard mapping, and highlights areas that are at high risk from riverine hazards. This combined information can inform an all-hazards approach to planning and policy.

Stormwater System

Previous studies identified linkages between the “natural” system (Dawson Creek), and the piped stormwater system. The stormwater system includes 46 outfalls that discharge into the Creek. The capacity for these outfalls to function is partially dependent on water levels within the Creek.

The stormwater drainage assessment found that out of the 46 outfalls that discharge to the Dawson Creek, approximately 10 could have their discharge capacities compromised even during a low magnitude flood (20% AEP). With progressively higher flood levels, more outfalls are potentially impacted. Based on the City’s *Drainage Master Plan*, these outfalls already experience surge conditions during the 20% AEP (5-year; 24-hr) design storm. Climate change is likely to exacerbate this secondary hazard, as well as those identified in the geomorphological assessment.

Mitigation Options Evaluation

The hydraulic model was developed to represent existing conditions, and therefore includes recent crossing upgrades at 15th St., 10th St., and 8th St. The results show that structural mitigation implemented post-2016 has reduced flood conditions. To address the City’s desire to reduce flooding specifically in the 102nd Ave. area, three high-level structural mitigation options were considered. These options were developed based on mitigation concepts that have previously been discussed by the City. They do not represent all possible options (e.g. non-structural solutions). However, they provide a strong indication of whether structural changes to the system will reduce flood hazards and warrant further study.

The *Upgrade* option simulated increased flow capacity at the 102nd Ave. crossing, the *Storage* option simulated an upstream reservoir to attenuate peak flows downstream (including in the City centre), and the *Combination* option was a version of the first two options.

The *Upgrade* option allows the moderately high magnitude flood (2% AEP) to be safely conveyed through the crossing and reduces backwatering. Under this option, a 12-m span structure would also reduce excess sedimentation (upstream) and erosion (downstream). The structure would allow for future channel migration at the crossing. However, the overall flood benefits of the *Upgrade* option are relatively localized.

It was determined that flows could be attenuated, and flood levels reduced by including a reservoir with a volume of 9,000 m^3 (the size of three and half Olympic-size swimming pools) upstream of the City centre. The impact of the reservoir on flood hazard is directly related to the volume of the reservoir. Larger reservoirs generally have larger challenges related to implementation, construction and maintenance. In light of these tradeoffs, the *Storage* option on its own has limited value.

The results show that the *Upgrade* and *Storage* options are complementary, meaning that combining both options would achieve flood benefits for the Dawson Creek channel—especially upstream of the 102nd Ave. area. The *Upgrade* and *Storage* options could be implemented on independent timelines. The combination approach can provide the City with flexibility as it manages flood while considering the dynamic and interconnected Creek system, and the uncertainties associated with climate change. To support decision making, it is recommended that the City better understand feasibility issues around the options such as costs, regulations, and timelines. Further, it is important that the City investigate additional options, including non-structural options, to reduce flood risk. The three structural options investigated in this evaluation confirm that they have some hydraulic merit, but only represent a small number of potential options that could reduce overall flood risk.

Recommendations

Building on the deliverables of this project, the following are recommended actions for the City:

- Use information from the flood mapping products to inform and update land use policies.
- Integrate secondary hazards associated with fluvial geomorphological processes into flood planning processes.
- Make the flood and fluvial geomorphological erosion mapping products public.
- Consider a mix of structural and non-structural mitigation options.
- Work with regional partners to improve flood hazard management regionally.
- Continue to collect hydrometric data.
- Integrate the hydraulic model into stormwater management planning.

Table 1: Summary of the technical approaches.

Task	Description
Hydrology Analysis	
Method	Delineation of 13 drainage areas using CDEM (0.75 arc-second resolution), and stormwater drainage plan. Flood frequency analysis of Water Survey of Canada (WSC) Kiskatinaw River station (07FD001), GEV distribution. Estimated project drainage area flows based on flood frequency analysis and WSC Dawson Creek (07FD015).
Flow Estimates (Existing Conditions)	50%, 20%, 10%, 2%, 1%, and 0.5%, and 2016 flood event (1.3%) AEP peak flows, for 13 drainage areas
Climate Change Consideration	Data from the Pacific Climate Impacts Consortium (2019): • Representative Concentration Pathway 8.5. • 6 general circulation models. Flood frequency analysis for 3 future periods compared to past (1966-2019): • 2021-2050 (2030s) • 2041-2070 (2050s) • 2071-2100 (2080s)
Hydraulic Modelling	
Topographic Inputs	Merged surface with down-sampled 0.5 m x 0.5 m horizontal resolution consisting of: • Field-collected bathymetry (July-September 2019)

Task	Description
	• LiDAR 2016 Vertical Datum: CGVD2013 Coordinate System: NAD83, UTM 10N
Method	1D / 2D HEC-RAS (Version 5.0.7): • Majority of crossings modelled (18) • All bridges, except 8th St., modelled in 1D • All culverts modelled in 2D Verification completed by way of comparison with 2016 flood extent derived from aerial photography and surveyed trash lines. Sensitivity runs completed to test Manning's n.
Flood Mapping	
Depth	Flood depths and extents: • Existing conditions: 50%, 20%, 10%, 2%, 1%, and 0.5% • Climate Change: 6 AEPs above for 2050s
Regulatory Flood Construction Level	0.5% AEP (existing conditions) plus 0.6 m freeboard
Hazard Severity	Depth x velocity (1 times factor for debris), for 0.5% AEP (existing conditions).
Fluvial Geomorphology	
Method	Channel overlay using ortho and satellite imagery (1959-2019). Field survey (August 2019).
Outputs	Channel morphology and fluvial processes. Identification of erosion hazard, and potential avulsion zones. Fluvial geomorphology map book.
Stormwater Drainage	
Method	Field survey (August 2019). Comparison of hydraulic model water levels with stormwater drainage system outfall locations and invert elevations.
Outputs	Identification of priority outfalls and backflow hazard based on design storm (20% AEP, 24-hr).

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List of Acronyms

AEP	Annual Exceedance Probability
BC	British Columbia
CDEM	Canadian Digital Elevation Model
CGVD	Canadian Geodetic Vertical Datum
CSP	Corrugated Steel Pipe
CSRS	Canadian Spatial Reference System
DEM	Digital Elevation Model
DFA	Disaster Financial Assistance
DGR	Dangerous Goods Route
DMAF	Disaster Mitigation and Adaptation Fund
DPA	Development Permit Area
EC	Existing Condition
EGBC	Engineers and Geoscientists British Columbia (formerly APEGBC)
EMBC	Emergency Management British Columbia
ID	Identifier
FBC	Fraser Basin Council
FMPR	Flood Mitigation Planning Report
FCL	Flood Construction Level
FHALUMG	Flood Hazard Area Land Use Management Guidelines
GEV	Generalized Extreme Value
GIS	Geospatial Information System
GCM	General Circulation Model
GNSS	Global Navigation Satellite System
HEC-RAS	Hydrologic Engineering Center River Analysis System
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
MO	Mitigation Option
MoTI	Ministry of Transportation and Infrastructure
NAD	North American Datum
NDMP	National Disaster Mitigation Program
OCP	Official Community Plan
PCIC	Pacific Climate Impacts Consortium
PCSWMM	Personal Computer Storm Water Management Model
POI	Point of Interest
PSC	Public Safety Canada
QGIS	Quantum Geographic Information System
RCP	Representative Concentration Pathway
RGS	Regional Growth Strategy
RTK	Real Time Kinematic
SWE	Snow Water Equivalent

UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction (formerly UNISDR)
UTM	Universal Transverse Mercator
VIC	Variable Infiltration Capacity
WSC	Water Survey of Canada
1D	One-dimensional
2D	Two-dimensional

1 Introduction

In recent years, flood events within the City of Dawson Creek (the City) have led to impacts to infrastructure and people in the community. The 2016 flood disrupted the City by affecting major crossings and restricting north/south travel. In response, the City and other levels of government have made a significant effort to manage flood impacts by spending millions of dollars on crossing upgrades, and hundreds of thousands on emergency response in the last few years alone. A larger strategic planning effort to reduce flood risk over time was impeded by the lack of a flood map, the foundational tool for flood management.

The goal of the current project is to provide flood mapping for the City that meets regulatory standards and guidelines, in order to support future planning and infrastructure decisions. The mapping exercise needs to consider a range of likelihoods of events, including under climate change.

This project builds on previously completed work presented within the Flood Mitigation Planning Report (FMPR), prepared by Ebbwater Consulting Inc. (2018). The FMPR established a flood risk reduction planning process that aligns with international best practice following the Sendai Framework for Disaster Risk Reduction[1]. One of the primary recommendations from the FMPR was to pursue grant funding under the National Disaster Mitigation Program (NDMP) to produce flood mapping. The City submitted an application and was successful.

Further, also building on learnings from the FMPR, the City recognized the importance of taking a watershed perspective in understanding hazards. The Dawson Creek watercourse and its urban watershed together form a dynamic and interconnected system that is affected by natural and human-caused processes. Therefore, supporting assessments were completed to describe hazards associated with erosion processes and the stormwater drainage system. This supporting knowledge will allow decision makers to consider watershed based tradeoffs related to mitigation options moving forward.

The FMPR and City staff and council have previously identified that parts of the City are particularly prone to flooding and flood damage. Structural changes, especially to crossings, have been implemented in some areas and proposed for others for many years. The hydraulic modelling associated with this project provided an opportunity to explore the efficacy of these mitigation options, and the City expanded the original scope of work to provide preliminary consideration of these options.

The development of flood mapping and the evaluation of mitigation options while taking a watershed perspective, is a multi-disciplinary endeavour. The City of Dawson Creek retained Ebbwater Consulting Inc. (Ebbwater) to lead the work. Ebbwater's team included Vector Geomatics Land Surveying Ltd. (Vector) and Palmer.

[1] The Sendai Framework for Disaster Risk Reduction is the global blueprint for disaster management. The Sendai Framework was developed by the United Nations in 2015. Weblink: https://www.undrr.org/implementing-sendai-framework/what-sf. Canada and BC are signatories to the framework.

1.1 Project Objectives

The information contained in this report is critical to support the City in key initial decisions regarding flood mitigation and capital cost allocations. The objectives of this analysis and report are as follows:

1. Produce flood mapping for Dawson Creek that meets current standards for the 0.5% annual exceedance probability event[2] (AEP), and that can be used to support activities ranging from public awareness to zoning and Official Community Plan amendments.
2. Assess hazards associated with fluvial geomorphology and stormwater drainage, which are related to the flooding of Dawson Creek. For erosion hazards (i.e., from fluvial geomorphology assessment), produce mapping of projected channel migration zones and potential avulsion locations to support activities ranging from public awareness to zoning and Official Community Plan amendments.
3. Apply the hydraulic model developed for flood mapping to assess structural options to mitigate flooding experienced at the 102nd Ave. crossing under a range of likelihood of events, and considering the watershed perspective.
4. Provide next steps and recommendations consistent with the City's flood risk reduction planning process.

1.2 Project Approach

This work followed the approach set out in the *Professional Practice Guidelines for Flood Mapping in BC*, henceforth referred to as the *Professional Practice Guidelines* (APEGBC, 2017). Materials being developed as part of the Federal Floodplain Mapping Guideline Series (Natural Resources Canada, 2018b) were also considered in the development of this report and associated maps. Where appropriate, other standards that, in Ebbwater's professional opinion, met or exceeded the bar set by provincial standards, were also used to inform this work.

1.2.1 Project Area

The City of Dawson Creek is located in northeast British Columbia (BC), and is named for the watercourse that runs through it. Dawson Creek is a tributary of the Pouce Coupé River, which flows north into the Peace River after crossing the BC-Alberta border. Prior to flowing into the Pouce Coupé River, Dawson Creek bisects the City. The project area's main channels are Dawson Creek and its main tributaries (South Dawson and Ski Hill Creeks).

Meeting the objectives of the project requires consideration of the larger Dawson Creek watershed and sub-watersheds to inform hydrologic analyses. These watersheds are outlined in black and shades of grey in Figure 1. The figure also shows boundaries for other tasks (e.g., fluvial geomorphology) included in this report. The other supporting project tasks are also shown in Figure 1, along with their assessment boundaries.

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[2] The annual exceedance probability (AEP) indicates the probability that an event will occur in any given year. The 0.5% AEP event has an indicative return period of 200 years. The concept is explained further in Section 2.3.

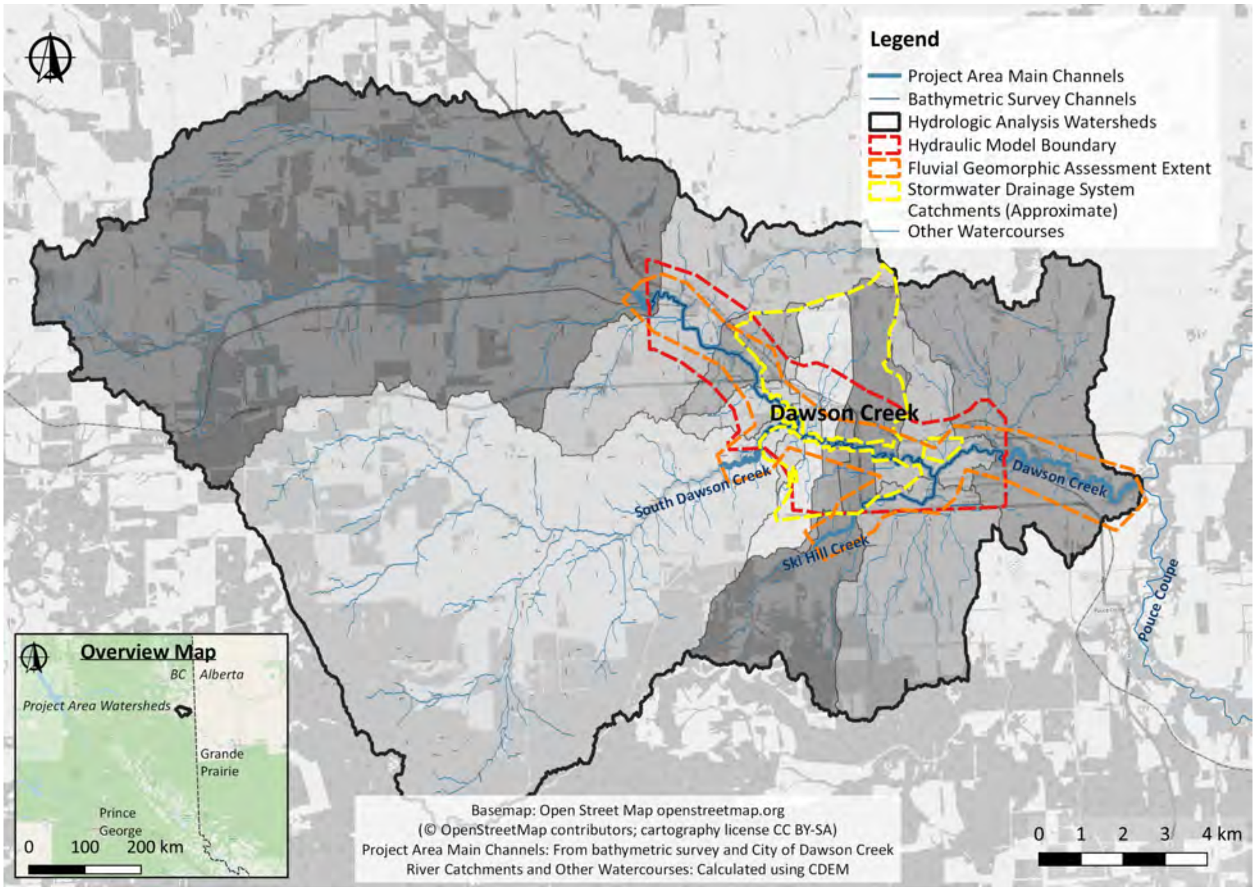

Figure 1: Project area watersheds with the boundaries associated with each task.

1.2.2 Project Tasks

Flood maps are technical tools that require significant amounts of data and diverse expertise to develop. They require an understanding of the surface over which water flows both overland (topography) and within a creek channel (bathymetry). Hydrologic studies of the watersheds and region are required to understand the volumes of water that are expected during flood events. These are used to support the development and use of a hydraulic model, which is then used to develop flood mapping. The nature of Dawson Creek specifically also requires an understanding of the geomorphology to inform erosion mapping, as well as of the interactions with the piped stormwater system.

The following provides an overview of the diverse tasks undertaken to achieve the objectives of this project. Brief descriptions of each project task are provided below, including details on their assessment areas and data resolution. The descriptions also highlight that both field-based data collection and desktop analyses were conducted. Figure 2 provides an overview of the approach by illustrating how the outputs from each task were interconnected.

Task 1: Topographic Surface Development. The bathymetric surveying completed by Vector Geomatics Land Survey Ltd. (Vector) focused on collecting detailed elevations in the Dawson Creek, South Dawson Creek, and Ski Hill Creek channels (the project area's main channels) and their crossing infrastructure. The objective was to develop an understanding of the shape of the main channels and the flood hazard area.

Field measurements were collected at intervals of 10–30 m along the channels. The bathymetry was then merged with a digital elevation model (DEM) (a model of ground levels in the local area) derived from LiDAR[3]. The final fully integrated DEM has a final horizontal resolution of 0.5 m. This merged topographic surface was used to support the hydrologic analysis, hydraulic modelling, and fluvial geomorphology assessment tasks.

Task 2: Hydrologic Analysis. Flows for Dawson Creek and major tributaries were estimated using regional hydrology information and available climate projections. The hydrology analysis provided flow inputs for the hydraulic model under various annual exceedance probability (AEP) scenarios, including under climate change.

Task 3: Hydraulic Modelling. A 2-dimensional (2D) hydraulic model was developed in HEC-RAS (a software) by using the merged DEM and hydrology as a foundation. Modelling was a key step in the project as it linked with all other project tasks. The model's upstream boundary was approximately at 223 Rd, and the downstream boundary was near the eastern end of the airport. The area included the South Dawson Creek and Ski Hill Creek tributaries. The total length of channel reach modelled was approximately 21 km.

Task 4a: Supporting Hazard Assessments – Fluvial Geomorphology. The objective of the assessment was to better understand the geomorphological form and processes of the main watercourses in the project area. Field reconnaissance provided an opportunity to observe areas of erosion, identify infrastructure at risk, and ground-truth desktop-based interpretations. The desktop component of the fluvial geomorphology assessment included review of historical and recent aerial photography, channel migration analyses, and erosion hazard mapping. The extent of watercourses assessed for the fluvial geomorphology assessment extended further upstream on Dawson Creek, South Dawson Creek, and Ski Hill Creek as well as extending downstream along Dawson Creek to the confluence with Pouce Coupé River. The total length of channel assessed was approximately 33 km.

Task 4b: Supporting Hazard Assessments – Stormwater Drainage. To complement the hydraulic modelling analysis, stormwater drainage was assessed at a high level, through both field and desktop analyses. The objective was to determine if there are specific discharge points that could be impacted by flood flows in the Creek, thus affecting the stormwater system. The assessment was based on the 46 locations where stormwater outfalls discharge to the Dawson Creek channel.

Task 5: Flood Mapping. Based on outputs from the hydraulic model, a series of flood mapping products were output for 6 AEP events, under existing and climate change conditions. A key deliverable is the regulatory flood map for the 0.5% AEP event, which was produced for existing conditions and under climate change. The climate change map is provided for a future period centered around the 2050s.

Task 6: Mitigation Options Evaluation. Output from the hydraulic model was used to explore 3 structural mitigation options to reduce flood depths and extents at the 102nd Ave. crossing. The evaluation was

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[3] LiDAR stands for Light Detection And Ranging and describes a survey method that uses remote sensing to map the surface of land.

completed at a conceptual level. Mitigation option 1 involved increasing the flow capacity at the 102nd Ave. crossing. Mitigation option 2 was the consideration of a storage reservoir to hold floodwaters and attenuate peak flows within Dawson Creek at a location upstream. Mitigation option 3 was a combination of the first two options. The evaluation included fluvial geomorphological considerations.

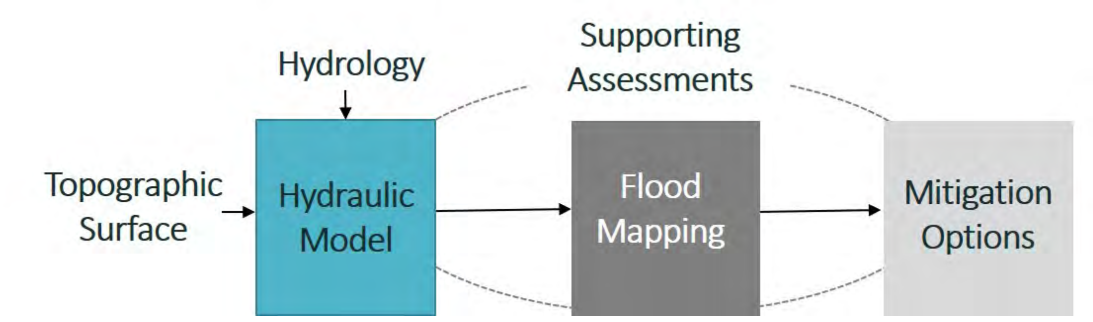

Figure 2: Flow chart of the project tasks and their interconnections. Flood mapping was the key deliverable of the project. The supporting assessments (i.e., fluvial geomorphology and stormwater drainage) provided a watershed perspective and were informed by the range of flood levels associated with modelled AEP events.

The approach shown in Figure 2 led to a strong understanding of flood hazard within the context of a dynamic and interconnected urban watershed system. This understanding is the basis for a risk-based approach to flood mitigation.

1.2.3 Project Challenges

This project was awarded and kicked-off in July 2019 under an aggressive timeline. At the onset of the project, the bathymetric surveying field work was initiated in earnest. However, this task was delayed due to frequent precipitation and high creek levels over the summer. These conditions increased the effort and time required to survey the bottoms of the project area's main channels.

Due to the high number of channel crossings (i.e., culverts and bridges) and the relatively small size of the creek, the hydraulic model proved to be challenging to setup and run. The crossings have important influences on channel hydraulics and required careful consideration.

In addition to the above project challenges, the evaluation of structural mitigation options was added to the scope of work after the project was awarded. Extra effort was required to represent the mitigation options within the model and to evaluate results.

Despite the above challenges, the project's objectives were met, and the recommendations were provided in a timely fashion to inform key decisions for the City.

1.3 Report Structure

This report starts by presenting a primer on flood hazard mapping (Section 2) followed by the project background (Section 3). The work to complete the topographic surface is then described (Section 4), as well as the hydrologic analysis (Section 5), which are both required inputs for the hydraulic model (Section 6). The mapping outputs from the hydraulic model are then presented (Section 7), followed by the fluvial geomorphology and stormwater drainage assessments (Section 8). The outputs from Sections 6 to 8 are used to evaluate the mitigation options (Section 9), which is followed by next steps including recommendations (Section 10), and conclusions (Section 11). A glossary and references are in Sections 12 and 13, respectively.

The report is supported by a series of appendices as follows:

- Appendix A: Topographic Surface Development
- Appendix B: Hydrology and Climate Change Background
- Appendix C: Hydraulic Model Documentation
- Appendix D: Flood Hazard Map Atlas
- Appendix E: Fluvial Geomorphology Assessment (Palmer)
- Appendix F: Stormwater Drainage Assessment and Channel Conditions Survey
- Appendix G: Flood Mapping Assurance Statement

2 Flood Hazard Mapping Primer

This section provides an introduction to flood hazards and flood mapping, and how these relate to flood management and planning. It provides background materials to support the understanding and interpretation of the main body of the report.

2.1 What is Flood Hazard?

A flood describes an event when areas that are usually dry become wet (i.e., a hazard); this can cause damage. However, not all flood hazards are created equal—flood hazard characteristics can differ in terms of water depth and velocity, frequency, onset, and duration. These characteristics affect how the flood hazard area in and the assets in it are impacted by flood. Therefore, it is important to understand as many aspects of the hazard as possible.

In the Dawson Creek area, the main flood hazard of concern results from riverine flooding of the Creek and its tributaries. However, secondary hazards also occur in conjunction with riverine flooding. Fluvial geomorphological processes such as erosion, induced by riverine flood hazards, can also cause damage. Pluvial (rainfall) events, can also cause flooding, especially in urban areas through the stormwater system.

2.2 Hazards of Interest

2.2.1 Riverine Flood Hazard

Riverine floods occur under a variety of conditions that cause a river to exceed its capacity and overflow onto its banks and into the flood hazard area (Figure 3). This can occur in small streams or large rivers, and the main driver is usually high runoff from heavy rain and snowmelt (as occurred in Dawson Creek in 2016, Figure 4). However, channel blockages such as debris can be important factors. In Dawson Creek, debris blockages occur at the many road crossings (i.e., bridges and culverts). This reduces the flow capacity under the crossing, which causes backwatering conditions upstream. Debris blockages from beaver dams occur in Dawson Creek. Ice jams are less frequent and of smaller concern.

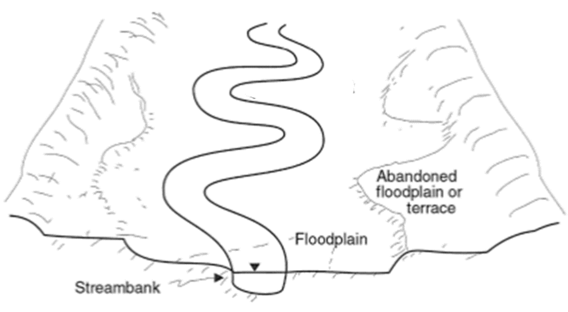

Figure 3: River channel and floodplain (Brooks, Folliott and Magner, 2013).

Figure 4: Dawson Creek bank overtopping during 2016 flood event (Source: City of Dawson Creek).

2.2.2 Fluvial Geomorphological Hazards

The energy associated with flood waters causes rivers to migrate gradually through time or shift suddenly (i.e., avulsions). Secondary hazards can result from slumping and erosion of the riparian zone and valley slopes. These hazards both affect, and can be affected by, infrastructure (Figure 5). Concentration of floodwaters through culverts or bridges at road crossings, such as at 102nd Ave. and 8th St., perturb natural geomorphological processes (e.g., sediment transport, lateral migration) and can exacerbate erosion near the crossing. As well, sections of river that are straightened, either by human activity or natural processes, reduce the volume of the channel and therefore the amount of flow it can accommodate.

Figure 5: Head of an active retrogressive slump near stored equipment on the bank of the Dawson Creek main channel. The slump may be triggered by fluvial erosion. Source: Palmer.

2.2.3 Pluvial Flood Hazard

Pluvial floods are caused when heavy rainfall soaks an urban drainage system, or natural soils, resulting in excess overland flow (runoff). They can be very localized depending on the rainstorm path. Extreme flooding can result with a combination of warm conditions and/or rainstorms occurring during mid-winter or spring snowmelt (freshet) seasons. The warm air and/ or rain leads to large volumes of snowmelt, which does not infiltrate due to frozen soils—resulting in high runoff rates (Maidment, 1992). These rain-on-snow events are exacerbated when they occur rapidly.

Figure 6: Stormwater drainage outfall susceptible to impact from high flood levels. Source: Palmer.

In urban areas, rainfall is collected and conveyed through a network of surface ditches and underground piping towards outfalls that freely flow into the creek (i.e., the stormwater drainage system). Under flood conditions, rising creek levels can prevent outfalls from discharging stormwater (Figure 6). These conditions can lead to secondary flood hazards caused by backflow or "surging" of upstream areas in the system.

2.3 Hazard Components

A natural hazard, such as riverine flooding, is generally defined by considering a hazard profile, which is made up of the flood hazard magnitude and the likelihood (probability) of the hazard occurring. Storm events have a range of likelihoods and associated magnitudes. Risk management professionals generally consider the risk associated with an event to be the product of the probability of it occurring and the consequences.

An understanding of the hazard profile is important when considering planning and response. A full flood hazard assessment requires an understanding of what will flood, and how likely this is. The work conducted as part of this project considered a variety of different hazard scenarios to support the concept of a hazard profile.

2.3.1 Flood Hazard Magnitude

There is a range of possible flood magnitudes from small events that remain in-channel, to much larger events that spill overland and cover large areas with water. The magnitude of flooding is best estimated through the development of detailed hydrologic and hydraulic analyses.

2.3.2 A Note on Hazard Likelihood

In addition to an understanding of where water will go in a flood, it is important to consider the likelihood of an event occurring. This is generally represented as an Annual Exceedance Probability (AEP), where the AEP refers to the probability of a flood event occurring in any year and where the probability is expressed as a percentage. For example, an extreme flood that has a calculated probability of 0.2% of occurring in this year (or any given year) is described as the 0.2% AEP flood. In the past, flood hazard likelihood was commonly represented as an X-year return period. However, this tends to cause confusion with lay people as to the frequency of an event with (e.g., it is commonly thought that if a 100-year flood has just occurred, it will not recur for another 99 years, which is not the case), and therefore best practice dictates the use of an AEP to describe flood likelihood.

Another way to think about flood likelihood is through the use of encounter probabilities, where it is possible to calculate the likelihood of encountering an event of a given size over a defined time period—for example, the length of an average mortgage (25 years) or the lifespan of a human (75 years). For instance for a 1% AEP flood, there is a 22% chance that an event of this size or greater will occur over a 25-year period, a 39% chance over a 50-year period, a 53% chance over a 75-year period, and a 63% chance over a 100-year period. Understanding the likelihood of an event, as well as the encounter probability of an event, can support decisions related to flood management.

2.4 What is a Flood Map?

Flood hazard maps are an essential tool to reduce flood risk as they provide a visualization of a flood hazard and an understanding of where and how deep water might be in a flood event. This can be used for understanding the current flood risk of an area and for planning to help ensure that flood risk is not increased. Flood maps are recognized as a necessary starting point for flood management.

Robust flood maps are produced by taking information from hydrologic and hydraulic models and calculations and applying these to base maps to show the extent of flooding. The *Professional Practice Guidelines* suggest that flood maps can show a variety of flooding effects, and depending on the purpose and budget of a project, this includes:

- **Flood Extent Maps.** These maps show the extent of the flood hazard area.
- **Flood Hazard Maps.** Hazard maps go beyond extent maps by providing information on the hazards associated with defined flood events, such as water depth, velocity, or duration of flooding.
- **Flood Risk Maps.** Risk maps reflect the potential damages that could occur as a result of a range of flood probabilities by identifying populations, buildings, infrastructure, residences, and environmental, cultural, and other assets that could be damaged or destroyed.

Flood maps can also include the following map types (Herbert, Picketts and Lyle, 2014):

- **Flood Event Maps**. Event maps document a specific flood event based on imagery and surveying at time of flooding. They can be used for future flood planning and to evaluate modelling results.
- **Flood Emergency Maps**. Emergency maps show basic information about the flood hazard area, as well as disaster response routes and evacuation zones.
- **Probabilistic Flood Hazard Map Series.** These depict a series of flood hazard maps showing hazard under various events.

The intent of this project is to develop a series of riverine flood hazard maps, as well as fluvial geomorphology hazard maps. Risk mapping was conducted at a high level, using primarily qualitative data sources in the FMPR. Detailed risk mapping requires additional information regarding the vulnerability of exposed elements in the flood hazard area and is not within the scope of this project. However, the refined mapping produced for this project could be used to produce updated and improved risk analyses and mapping.

2.5 Guidance for Flood Mapping

In BC, flood mapping guidance is contained in the Engineers and Geoscientists British Columbia (EGBC, formerly APEGBC) *Professional Practice Guidelines for Flood Mapping in BC*, released in 2017 and referred to in this report as the *Professional Practice Guidelines* (APEGBC, 2017). Flood mapping guidance is also provided at a federal level in the *Federal Flood Mapping Guidelines Series*. This guidance series is still under development with some sections still to be released (Natural Resources Canada, 2018a). The documents that have been released include technical guidance on LiDAR collection, geomatics, and hydrological and hydraulic assessment (Natural Resources Canada, 2019a; 2019b). These guidelines along with the *Professional Practice Guidelines* provide recommendations as to how flood maps should be produced and what should be included in these maps. This guidance has been applied to this project.

2.5.1 Water Levels and Terms used in Flood Mapping and Flood Planning

Under the *Act,* local governments are *required to consider* the provincial Flood Hazard Area Land Use Management Guidelines (FHALUMG) (FLNRORD, 2018). Originally released in 2004, the FHALUMG are provincial guidelines that were intended to help local governments, land use managers and approving officers develop and implement land use management plans and make decisions for flood hazard areas. These guidelines define a number of key water levels to be used in flood planning and mapping. These terms are used throughout this report and in mapping deliverables.

Designated Flood. The FHALUMG defines the designated flood to be used in the calculation of FCLs as 0.5% AEP, based on a frequency analysis of unregulated historic flood records or on regional analysis where inadequate streamflow data are available.

Designated Flood Level. The designated flood level is the observed or calculated flood level for the designated flood.

Flood Construction Level (FCL). The FCL is an elevation relative to the Canadian Geodetic Vertical Datum (CGVD), and it is used in planning to establish the elevation of the underside of a wooden floor system (or top of concrete slab) for habitable buildings. It includes a freeboard (for safety) to account for uncertainties in the analysis.

FCL = Designated Flood Level + Freeboard

2.5.2 Freeboard

A freeboard is a vertical distance that is added to water levels as a safety margin to account for uncertainties in the calculation of and localized increases in water levels. The *Professional Practice Guidelines* state that appropriate freeboard to apply to extent maps to obtain FCL values ranges between 0.3 and 1.0 m, depending on the uncertainties in the extent mapping and the risk tolerance of the regulating jurisdiction.

The *Professional Practice Guidelines* recommend that typical freeboard values for "water" floods that have been adopted in BC are 0.3 m above the maximum instantaneous design flood level or 0.6 m above the mean daily design flood level (whichever is higher). Larger freeboards are appropriate where there is potential for debris floods, debris flows, ice jams, debris jams, sedimentation and other phenomena that are harder to predict.

For the purpose of this study we have applied a more conservative freeboard of 0.6 m to define Flood Construction Levels.

2.6 Legislative Framework

The following is provided to guide the City on how flood maps can be incorporated into plans and policy.

In BC, the *Local Government Act* and *Land Title Act* were amended in 2003 and 2004 to remove the role of the Minister of Environment from flood hazard area designation and approving administration, shifting the authority to local governments. Due to this change, local governments have an increasingly important role to play in the management of flood hazards and gain this authority from the provincial legislation—the *Community Charter* and the *Local Government Act*.

Community Charter [2003]

The *Community Charter* provides the statutory framework for local governments within the province of BC; it sets out areas of authority and procedures. Of relevance to flood management are the provisions with Division 8 of the *Charter* that set out the authority of local government to have a Chief Building

Inspector permit buildings and occupancy of structures, and to require certification of a *qualified professional*[4] that "land may be safely used" in areas subject to flood (and other hazards).

The use of the *Community Charter* generally requires base information from flood mapping (either extents or extents and flood depths or FCLs) to support the Chief Building Inspector and qualified professionals to determine if a site and/or building is safe for intended use. In the absence of an approved flood map, this statute still provides a local government's Chief Building Inspector with the ability to require a report to be prepared by a qualified professional for new buildings and for structural alteration or addition to an existing building or structure.

Local Government Act [2004]

Where flood mapping is available, this statute provides both policy and regulatory provisions that can be implemented as stand-alone provisions or collectively to form a framework to effectively manage flood hazard areas. Specific tools available under the *Local Government Act* relevant to flood management are:

1. **Regional Growth Strategy (RGS) Bylaw.** A strategic plan that defines a regional vision for sustainable growth. Policies can be incorporated into an RGS to prepare for climate change by supporting adaptation strategies and by allowing for sea level rise to the year 2200 and beyond.
2. **Official Community Plan (OCP) Bylaw.** A guiding policy document used to inform land use decisions. OCPs can include policies in support of climate adaptation and strategies to mitigate sea level rise.
3. **Development Permit Areas (DPAs).** Designated areas requiring special treatment. An Official Community Plan may designate DPAs for specified purposes, including the protection of development from hazardous conditions. Hazard DPAs are generally triggered by alterations to the land associated with development activities. DPAs must include contributions or objectives that justify the designation and must also provide guidelines for developers and homeowners to meet the requirements of the DPA.
4. **Flood Bylaw.** If a local government considers that flooding may occur on land, the local government may adopt a bylaw to designate a flood hazard area and specify flood levels for it, establish setbacks and construction elevations for habitable space for new buildings and structures, and for landfill within the flood hazard area [Section 524]. Most often, applications for building permits trigger flood bylaw requirements.
5. **Zoning Bylaw.** Land use zoning bylaws are used to regulate the use of individual parcels of land, including parcel configuration, the density of the land use, and siting and standards of buildings and structures [Section 479]. These bylaws have been used historically for flood hazard areas to ensure public safety is maintained by limiting the types of uses associated with those lands.
6. **Subdivision Bylaw.** Standards for subdivision design can be established by local governments (within the *Provincial Guidelines)*. In the case of Regional Districts, the approving authority for

[4] In the case of the *Community Charter*, a *qualified professional*, is defined as "(a) a professional engineer, or (b) a professional geoscientist with experience or training in geotechnical study and geohazard assessments".

subdivision is the Ministry of Transportation and Infrastructure, which is required to consider the *Provincial Guidelines* to determine the conditions for subdivision approval.

7. **Local Building Bylaw.** There is also provision under [Section 694] of the *Local Government Act* for a local building bylaw or permit process to require floodproofing. Generally, these are no longer used as the updated BC Building Code has some provisions for floodproofing and any additional conditions can also be integrated into a flood bylaw. It should also be noted that the National Research Council of Canada and partners are working to incorporate new floodproofing standards into future iterations of the Canadian Building Code.

2.6.1 City of Dawson Creek Legislation and Policy

The City of Dawson Creek currently manages its responsibilities for flood hazard management under section 4.16 of the 2019 Master Zoning Bylaw, and through the *Local Government Act* through DPAs within their Official Community Plan (OCP). The City is in the midst of updating and refining the OCP, including consideration of policies to reduce flood risk. A placeholder flood map is currently included in the 2018 OCP (March 2019 amendment). The intent of this current project is to provide mapping and tools to support finalisation of this policy update.

2.7 Provincial Direction on Disaster Risk Reduction

As stated, the *Local Government Act* includes provisions that enable local governments to manage development in relation to lands prone to flooding. In doing so, the local government must give consideration to the Provincial Flood Hazard Area Land Use Management Guidelines (the *Provincial Guidelines*). The guidelines are intended to minimize injury and property damage resulting from flooding and are linked to the Provincial Compensation and Disaster Financial Assistance Regulation. Together, the Provincial Regulation and Guidelines are used to determine if property has been adequately protected and whether a local government is eligible for financial assistance following a flood event.

A more recent development in BC, mostly stemming from the criticisms and recommendations in the 2018 report on the findings of the 2017 BC Flood and Wildfire season (Abbott and Chapman, 2018), is the commitment to adopt the Sendai Framework for Disaster Risk Reduction [5] (UNISDR, 2015). The Government of Canada endorsed Sendai in 2015, and in late 2018, the Government of British Columbia announced that it would also adopt Sendai, stating, "Canada is already a signatory to the framework and the Province will now also adopt the framework to align and improve our approach to all phases of emergency." (Emergency Management BC, 2018). In late 2019, BC initiated a process to incorporate the Sendai Framework principles into the *Emergency Program Act*[6].

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[5] United Nations International Strategy for Disaster Reduction (UNISDR): Sendai Framework for Disaster Risk Reduction 2015-2030; http://www.unisdr.org/we/coordinate/sendai-framework.

[6] The BC *Emergency Program Act* closed its comment period on a discussion paper in January 2020. Weblink: https://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/emergency-preparedness-response-recovery/modernizing_bcs_emergencymanagement_legislation.pdf. A "What We Heard" report is scheduled for release in spring 2020, and the legislation is planned to be introduced in fall 2020 and legislated in spring 2021.

The Sendai Framework is the new global blueprint for building disaster resilience; it is supported by the United Nations. The goal of the framework is to prevent new and reduce existing disaster risk. This is promoted through four priorities for action:

1. Understanding disaster risk.
2. Strengthening disaster risk governance.
3. Investing in disaster risk reduction for resilience.
4. Enhancing disaster preparedness.

Sendai provides a framework to support all levels of government, including local governments, to increase their resilience to both chronic and acute shocks.

This direction is relevant to Dawson Creek as it works to develop plans and policies to mitigate flood impacts. In the short term, it is important to note that the new direction from senior government is a shift towards risk-based planning and policy, as opposed to the hazard-focused policy outlined in previous sections (i.e., regulatory tools that require designation of a specific hazard area). A risk-based approach requires consideration of the impacts and consequences of flood (as presented at a high-level in the FMPR) so that different treatments can be applied for different types and severities of impact. Further, a true risk-based approach considers a variety of hazard scenarios (and not a single hazard event—0.5% AEP—as is the current practice). This project will produce an atlas of scenarios to support this type of work in the future.

3 Project Background

3.1 Flood Risk Reduction in the City of Dawson Creek

The FMPR established a long-term view of flood mitigation as an 8-step planning process that takes a community from the acknowledgement of the flood hazard through to an implementation plan. Details on this process, as a best practice approach, are found in the FMPR. The process integrates specific timelines, budgets, and monitoring of measures of success. Progress and key messages from the FMPR, based on each step of the planning process, are summarized in Table 1. The table also indicates how this flood mapping project relates to the planning process.

Table 1: High-level summary of progress on risk reduction, based on the FMPR and the current flood mapping project.

Step	Flood Mitigation Planning Report % Progress and Key Messages		Consideration Within Flood Mapping Project
1. Acknowledge problem and set the stage	100%	Multiple stakeholder and public workshop events, as well as ongoing engagement were held to progress and complete this step. Residents in the community **care deeply about flood impacts**, which are **complex**.	None required.
2. Identify and establish hazards	50%	This was achieved, along with other studies (Urban Systems, 2017a) at a high-level. However, **future refinement was recommended** to develop models and mapping suitable for non-structural flood planning that also meets current standards and guidelines.	A hydraulic model was developed and applied to complete flood mapping that meets current standards and guidelines. Supporting hazard assessments (i.e., fluvial geomorphology and stormwater drainage) provide a watershed perspective.
3. Identify exposure and vulnerability	95%	This was nominally achieved and needs to be refined in future as information is improved. The City needs to contend with **specific geographic challenges**.	Not relevant during this phase of work (see Step 8).
4. Identify consequence and risk	95%	This was nominally achieved. And needs to be refined in future as information is improved. **Risk was determined to be moderate to high**.	Not relevant during this phase of work (see Step 8).

Step	Flood Mitigation Planning Report % Progress and Key Messages		Consideration Within Flood Mapping Project
5. Establish objectives and measures of success	50%	Preliminary information to support this step was gathered. **People in Dawson Creek clearly want a safe and prosperous community to live in now and in the future**.	A watershed-based understanding of primary and secondary flood-related hazards will facilitate the completion of this step in the future.
6. Identify flood mitigation options	50%	A range of adapt, protect, and retreat mitigation strategies were identified (e.g., regulatory, engineering, building controls, emergency planning and management, and economic actions), and **it was recommended that non-structural options be considered in conjunction with structural options.**	With the development of the hydraulic model, the City wanted to run simulations of a limited number of structural mitigation options to address issues specific to the 102nd Ave. area.
7. Identify preferred options	5%	Generic examples of flood mitigation options were presented for discussion in Dawson Creek. A high-level screening asserted that **all options be considered at a high-level in all planning projects**.	While preferred options may be identified within the limited number of structural options assessed, a greater set of options should be assessed in future studies.
8. Develop Adaptive Implementation Plan	0%	None.	This step is to be completed following this flood mapping project and should include refinement of Steps 3 to 7.

The effort to advance flood risk reduction in this project is focused on completing flood mapping and related hazard assessments (Step 2 in Table 1). The project also includes an evaluation of structural mitigation options (part of Steps 6 and 7 in Table 1). As a whole, the project brings the City closer to the longer-term goal of flood risk reduction by continuing the 8-step planning process.

3.2 Physical Setting

Dawson Creek and its tributaries flow along the bottom of a former glacial lake impounded at the margin of the retreating Laurentide Ice Sheet during the deglaciation of the region roughly 10,000 years ago. The channels have incised into the erosion-prone, fine-grained sediments (sand, silt, and clay) deposited on the bottom of the glacial lake. Long-term incision has formed a well-defined valley along the Dawson Creek downstream of its confluence with the South Dawson Creek.

The watersheds that drain into the City of Dawson Creek's urban area are much larger than the City itself (see project area watersheds in Figure 1), covering an area of approximately 250 km^2. Land use in the project area watersheds is mixed and consists primarily of the following: cropland (28%), grass (26%), trees (31%), and urban areas (12%). The agricultural lands predominate in areas upstream of the City. These headwater tributaries have been largely realigned and straightened. Within the City, Dawson Creek and Ski Hill Creek have also undergone similar anthropogenic (human-caused) changes associated with urban development since the 1950s. Fill has been placed within the Dawson Creek valley to facilitate urban development. In the South Dawson Creek watershed, there has been urbanization over the past 50 years, but the channel has remained relatively unaltered.

In terms of climate, temperatures in the City range from a mean summer temperature of 15°C to a mean winter temperature of -14°C. Mean annual precipitation ranges from 350 to 600 mm[7]. The City experiences cold winters with snow accumulation and low flows. During the spring snowmelt (freshet) season, high flows can occur as a result of melting snowpack. These conditions can be exacerbated by heavy rainfall events.

In the last decade, Dawson Creek has experienced flooding in 2011, 2016, and 2018. In the Dawson Creek area, flood response has included developing a better understanding of flood hazard and risk through the completion of the Urban Systems (2017b, 2017a) and Ebbwater (2018) studies. Hydrotechnical and design studies have also been completed by the Government of BC to support infrastructure reconstruction within the area. These studies are discussed in more detail in Section 5.

3.2.1 Climate Change in the Region – Past Trends

Climate change is a key consideration in the project area. Trends over the last century show statistically significant increases in temperatures annually and during winter and summer seasons (Ministry of Environment, 2016), as shown in Table 2. Combined with clear changes in annual precipitation, this will affect flow timing and volume. With continued warming, less precipitation is expected to fall as snow leading to smaller snowpacks and earlier freshets. Higher peak flows are possible due to more extreme storms and continued rain-on-snow events (FBC, 2019). Historical and projected peak flows are discussed in detail in Section 5.5.

[7] City of Dawson Creek Website. Climate. Weblink: https://www.dawsoncreek.ca/business-community-profile/community-profile-climate/. Accessed 10 December 2019.

Table 2: Historic climate change trends for the Boreal Plains Ecoprovince (adapted from Ministry of Environment, 2016). The trends are based on the period 1900–2013.

Temperature (°C/century)	
Annual	+1.7
Winter	+2.9
Spring	Not significant[1]
Summer	+1.4
Fall	Not significant[1]
Precipitation (%/century)	
Annual	+14
Note 1: Refers to a lack of a statistical trend that is significant at the 95% confidence interval	

3.3 Watershed Perspective

A risk-based approach to flood management requires consideration of a broad set of water-related issues. Public safety, infrastructure, and environment all need consideration at the watershed scale. Further, these issues must be considered with an understanding of river dynamics, responses to environmental changes, and varying levels of human-caused disturbances (e.g., changes in land use, river straightening, and dredging).

Rivers evolve as a result of natural and human-caused changes through fluvial geomorphological processes, such as erosion and deposition. Flood management needs to respect this dynamic balance, as well as recognize that it is being disrupted by climate change. Factors affecting hydrology, such as temperature, precipitation (including intensity, duration, and volume), and land use could impact rivers and their natural geomorphological processes in the decades to come (Biron *et al.*, 2014).

In Dawson Creek, hazards such as erosion could be worsened by flooding, increasing the potential to cause damage. Surcharging of the stormwater drainage system is another hazard that could potentially result from flooding. These represent a limited but important set of issues that are considered within this project through a watershed perspective. Adopting this perspective is part of a proactive approach, in contrast to reactionary approaches that lead to typical structural-based reconstruction following large flood events. The watershed perspective will better equip the City to make flood mitigation decisions, and to build community resilience.

3.4 Summary

This project builds on the technical studies completed to date and follows the risk reduction planning process established in the FMPR to help the City better understand flood hazard through mapping. In addition to the development of flood mapping, the project includes an evaluation of mitigation options. The diverse steps taken to complete these analyses (summarized in Figure 2) are described in the following sections, starting with the topographic surface development.

4 Topographic Surface Development

Surveying of creek channel sides and bottoms (bathymetry) and of overland flood hazard areas (topography) and the subsequent development of a merged digital elevation model (DEM) were necessary to provide a continuous surface for input to the hydraulic model.

To support the development of a topographic surface, LiDAR data were available for the project area, which were collected in 2016 and 2019 for the City. LiDAR is an excellent resource for hydraulic modelling, as the technology is applied to create a high resolution representation of the ground surface at relatively low cost (Wedajo, 2017). However, the LiDAR beam does not penetrate water, meaning that LiDAR surfaces do not represent creek bathymetry.

In order to develop bathymetry, field data collection was required. An extensive survey program to collect bathymetric information along the main creek channels was conducted. This information was then used to create a merged DEM for the project area. These activities were completed by Vector Geomatics Land Surveying Ltd. The activities are summarized below, and details are provided in Appendix A.

4.1 Bathymetric Surveying

A field survey was completed from 17 July to 3 September 2020. The purpose of the survey was to collect channel cross-sectional elevations along the main channels (bathymetry) within the project area. Under ideal conditions, this survey would be completed during low-flow (dry) conditions to allow the field surveyors to easily walk across channels. Unusual summer rainfall in the Dawson Creek area extended the original field schedule, as crews had to wait for flows to drop or had to employ alternate survey techniques.

Figure 7: Surveying the creek bottom near the Dawson Creek Golf and Country Club using a reach rod attached to an RTK. 19 July 2019. Source: Vector.

The survey was completed using a real time kinematic (RTK) positioning device using the global navigation satellite system (GNSS), and reach-rods were used on small bridge decks (Figure 7). The field team also used a single-beam sounder to collect water levels for channel sections that could not be waded across. Setting up the single beam sounder was challenging in many reaches due to the presence of beaver dams and their debris, which caused channel breaks. Well over 40 beaver dams were recorded in the project area's main channels.

Culvert inverts, soffits, and locations were recorded. Bridges were surveyed to capture the low and high chords, as well as the location and width of pillars and/or abutments. These measurements were recorded to later represent these structures within the hydraulic model (Section 6.2.5).

The field survey data were calibrated with the Dawson Creek control point (DC001) located in the parking lot of City Hall. The field survey points were checked against the two LiDAR surfaces, with error residuals within +/- 4 cm.

4.2 DEM Merging Process

A new DEM was produced by merging the 2017 LiDAR data flown in September 2016 and obtained by the City of Dawson Creek (McElhanney Consulting Services Ltd., 2017), and the surveyed bathymetry data. The approximately 14,000 bathymetric data field survey points were imported into AutoCAD software and a series of pre-processing steps were conducted. A 2-dimensional surface was created using the Canadian Geodetic Vertical Datum of 1928 (CGVD28), which was then overlaid with the LiDAR surface.

The LiDAR surface consisted of 150 tiles (1 km x 1 km in size each) and used the Canadian Geodetic Vertical Datum of 2013 (CGVD2013)[8]. The LiDAR surface and the bathymetric surface overlapped with 19 of those tiles. For the overlapping tiles, the bathymetric data were swapped with the LiDAR surface. The merged surface was gridded, and then down-sampled to a horizontal resolution of 0.5 m. The final merged DEM (Figure 8) included the bathymetric information for a 21-km reach of Dawson Creek, Ski Hill Creek, and South Dawson Creek. No bathymetric data for the other small tributaries within the project area were incorporated within the DEM. The merged DEM elevations were referenced in Metric and projected in NAD 83 (CSRS) UTM Zone10N, using the CGVD2013 vertical datum.

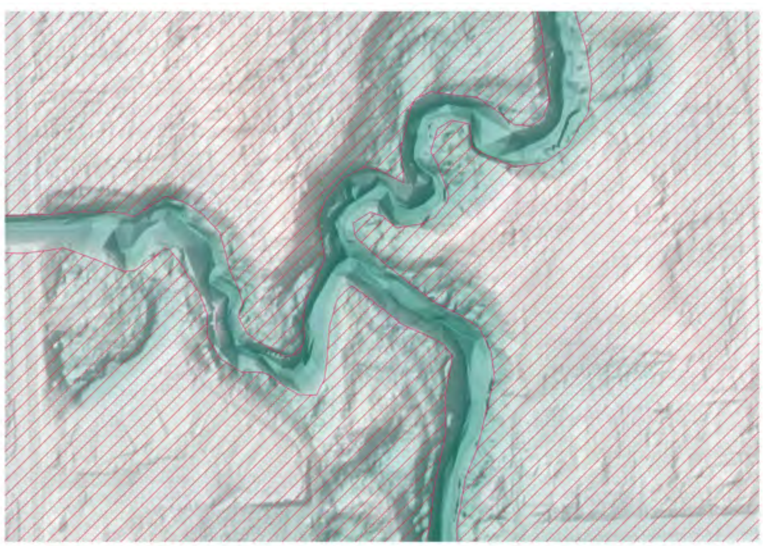

Figure 8: Example from the project area showing the merged LiDAR and bathymetric data (final topographic surface). The LiDAR data coverage is distinguished by the area with diagonal red lines, and the bathymetric data corresponds to the channel areas.

[8] Differences between the CGVD28 and CGVD2013 vertical datums is discussed in Section 7.4 (Flood Mapping Limitations).

5 Hydrologic Analysis

The objective of the hydrologic analysis was to estimate how much water will enter the project area's main channels, which are simulated in the hydraulic model. The amount of water entering a channel through time is depicted by a hydrograph and varies depending on factors such as the drainage area, land characteristics (topography, land use, soil) and climate. Furthermore, in urban settings like the City of Dawson Creek, the stormwater system controls where flows are discharged to the main channel through outfalls.

Hydrometric monitoring stations are key data sources that provide historical records of observed flows for specific locations on a river. The information can be analyzed, translated, and used as inflow points for the hydraulic model boundaries. If no, or only very short, historical river flow records exist, information from hydrometric stations in watersheds within the region can be used to infer flows.

For flood hazard modelling, the flows of interest are the extreme high flows (also called peak flows). Due to the relatively infrequent occurrence of these events, they are not well represented in hydrometric records, which typically cover short time periods.

To address this issue, flood frequency analysis was used to estimate peak flows for different likelihoods of occurrence. In this statistical method, a curve was fitted to the observed peak flows, which established a relationship between the observed peak flow and its likelihood to occur (this curve is called a frequency distribution). The curve was then extrapolated to estimate extreme peak flows that had not yet been observed in the hydrometric record. However, this analysis was based on historic records, and as the climate is changing, peak flows are also likely to change. The peak flows of interest in this study are the flows related to the 50%, 20%, 10%, 2%, 1%, and 0.5% AEP, for the existing conditions as well as for future time periods with climate change consideration.

This section provides the background on the hydrological analysis to determine the inflows of water into the hydraulic model, for a range of existing conditions and future scenarios, considering both more frequent (smaller) and very rare (larger) peak flows. First, previous hydrologic studies in the region are discussed (Section 5.1). The next section describes how the drainage areas were delineated to estimate the inflows into different hydraulic model boundaries (Section 5.2), followed by information on the available hydrometric data in Dawson Creek (Section 5.3). Section 5.4 describes then how the historic peak flows were estimated, and Section 5.5 describes how these may change under climate change. Lastly, Section 5.6 discusses the limitations of the study.

5.1 Previous Hydrologic Studies in the Region

Several previous studies have been conducted on the hydrology of the region. In 2016, Urban Systems estimated the 0.5% AEP flows as part of the *Dawson Creek Channel Assessment Post-June 2016 Flood* (Urban Systems, 2016, 2017a). Considering the short hydrometric data record for Dawson Creek, they used observed peak flows from 11 regional Water Survey of Canada (WSC) hydrometric stations within the Alberta Plateau area, extending from the mountain foothills west of Dawson Creek to up to 200 km eastward into Alberta. They fit a frequency distribution (of the Gumbel type) to the annual peak flows for each station, and based on that, developed a regional flood curve for each AEP scenario (a regional flood curve relates peak flows to the drainage areas of hydrometric stations, and can then be used to estimate peak flows for a known drainage area). Urban Systems then used the developed regional flood curves to estimate peak flows for Dawson Creek.

In 2017, also in response to the 2016 flood, the Ministry of Transportation commissioned a *South Peace Recovery Program Report on the 2016 Event and Regional Hydrology* (NHC, 2017). The study updated regional rainfall statistics and regional flood curves, described the historical context of the 2016 flood, and estimated potential impacts of climate change on rainfall and streamflow. The analysis focused on providing regional flood curves for two regions, one of which is of interest to this project (the low relief, Alberta Plateau watersheds, which contains the Dawson Creek watershed). For the development of the regional flood curves, they tested 14 WSC hydrometric stations across the Alberta Plateau region (reaching approximately 200 km into Alberta). They concluded, however, that most of these stations were not representative of the hydrological conditions in the Alberta Plateau watersheds in British Columbia. Their final regional curve therefore excluded 10 of the 14 stations, and it was fit to the following 4 regional stations: Kiskatinaw River (WSC 07FD001), Pouce Coupé River (WSC 07FD007), Dawson Creek (WSC 07FD015), and Grimshaw Drainage (WSC 07FD908). For their climate change impact analysis, they used hydrological modelling output from the Pacific Climates Impacts Consortium (PCIC) based on the 4th Assessment Report (AR4) from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007), which was available at the time of analysis.

In the time since the above study was conducted, PCIC has updated the climate change analysis for the region using the output of the 5th Assessment Report (AR5) from the IPCC (IPCC, 2013). In this updated analysis, PCIC extended their hydrological modelling boundary to include the Northeast region of BC (which contains the project area) (FBC, 2019). PCIC applied the Variable Infiltration Capacity (VIC) model, which represents various water flow and storage components in a watershed (rainfall, soil infiltration, surface runoff, evapotranspiration, as well as snow accumulation and melt) at a ~30 km^2 resolution. It is a large-scale hydrological model aimed to provide regional results.

Lastly, the University of Northern British Columbia is also in the process of developing a study on the storm evolution and AEPs of the June 2016 flood event in the Northern Rockies (Sharma, 2019). However, final results are not yet available.

Despite the availability of previously completed hydrological analyses, the analysis results have limitations in time and space that make them unsuitable for estimating local hydrology in Dawson Creek for the purpose of flood hazard mapping. The Urban Systems (2017) analysis was conducted before the extreme flows of the 2016 flood were available. Data from this storm event are critical to be included within the flood frequency analysis and would likely change the frequency distributions presented in that study. Further, the study used many regional stations that were not considered hydrologically representative by later analyses (see NHC study and later in this report). The NHC (2017) study focused on providing regional flood curves, and given the limited number of hydrometric stations, developed regional flood curves with only a small number of hydrometric stations. This can lead to high uncertainties, especially for drainage areas of the size of Dawson Creek for which a short hydrometric record was used. The study did not include the 2016 flood flows (which were unavailable at the time the analysis was completed). Therefore, for this project, a detailed hydrological analysis was required to provide input to the hydraulic model and flood hazard mapping. The hydrologic analysis also included a climate change analysis that incorporated the most updated projections from PCIC.

5.2 Delineation of Drainage Areas for Hydraulic Model Inflows

The watershed area of Dawson Creek and its tributaries is larger than the hydraulic model boundary, as the hydraulic model focuses on the urban area, comprising the Dawson Creek main channel, as well as South Dawson and Ski Hill Creeks (i.e., the project area's main channels) (see Figure 9). The flows generated within the larger watershed area require consideration, as these are inflows to the hydraulic model. These inflows include the project area's main channels, as well as the inflows from smaller tributaries and the City's stormwater drainage system. As there are no streamflow data available for all of these different inflows, the flows were estimated based on their drainage area, which is standard practice for the purpose of input to hydraulic modelling.

The first step for the drainage area analysis was to determine the upstream contributing areas of each of the model inflow points. This analysis was based on topography and the concept that sub-basins are delineated based on hydrological flow paths across the landscape. For topographic information, the Canadian Digital Elevation Model (CDEM)[9] was used with the highest available resolution of 0.75 arc-seconds. Note that the higher resolution 2016 LiDAR data (see Section 4) could not be used for this analysis, as topographic information for the entire Dawson Creek watershed was required, whereas the LiDAR data extent is confined to the urban area of the City.

Next, the geographic information systems (GIS) software *Whitebox* (Lindsay, 2016) was used to ensure that the DEM allowed hydrological flow paths and removed any depression artifacts in the DEM (a process called hydrological-conditioning). The stream network was delineated, as well as the outline of the Dawson Creek watershed and its sub-basins for all the tributaries in *Whitebox*. Then the SAGA (System for Automated Geoscientific Analyses) plug-in in the QGIS software (Conrad, O. et al., 2015; QGIS Development Team, 2019) was used to delineate the upslope areas for each of the hydraulic model inflow points along the project area's main channels (Figure 9, Table 3).

This analysis provided all the inflows for open channel watercourses. However, the City has an extensive stormwater drainage system, and outflows of the drainage system into the main watercourses needed to be captured accurately as well. Therefore, the *Drainage Master Plan* (OPUS, 2017) and the representation of outfalls, pipes, and sub-catchments in the PCSWMM model (Section 8.2) was assessed. To reduce the number of hydraulic model inflow points, outfalls located between each bridge were grouped, with the goal of representing total flows occurring through bridges. For inflow points that contained a mix of inflows generated from outfalls as well as open channels, the drainage areas for that inflow point were combined (Table 3).

[9] Government of Canada (2020): Canadian Digital Elevation Model (CDEM); 0.75 arc-second resolution. Downloaded 16 January 2020 from https://maps.canada.ca/czs/index-en.html.

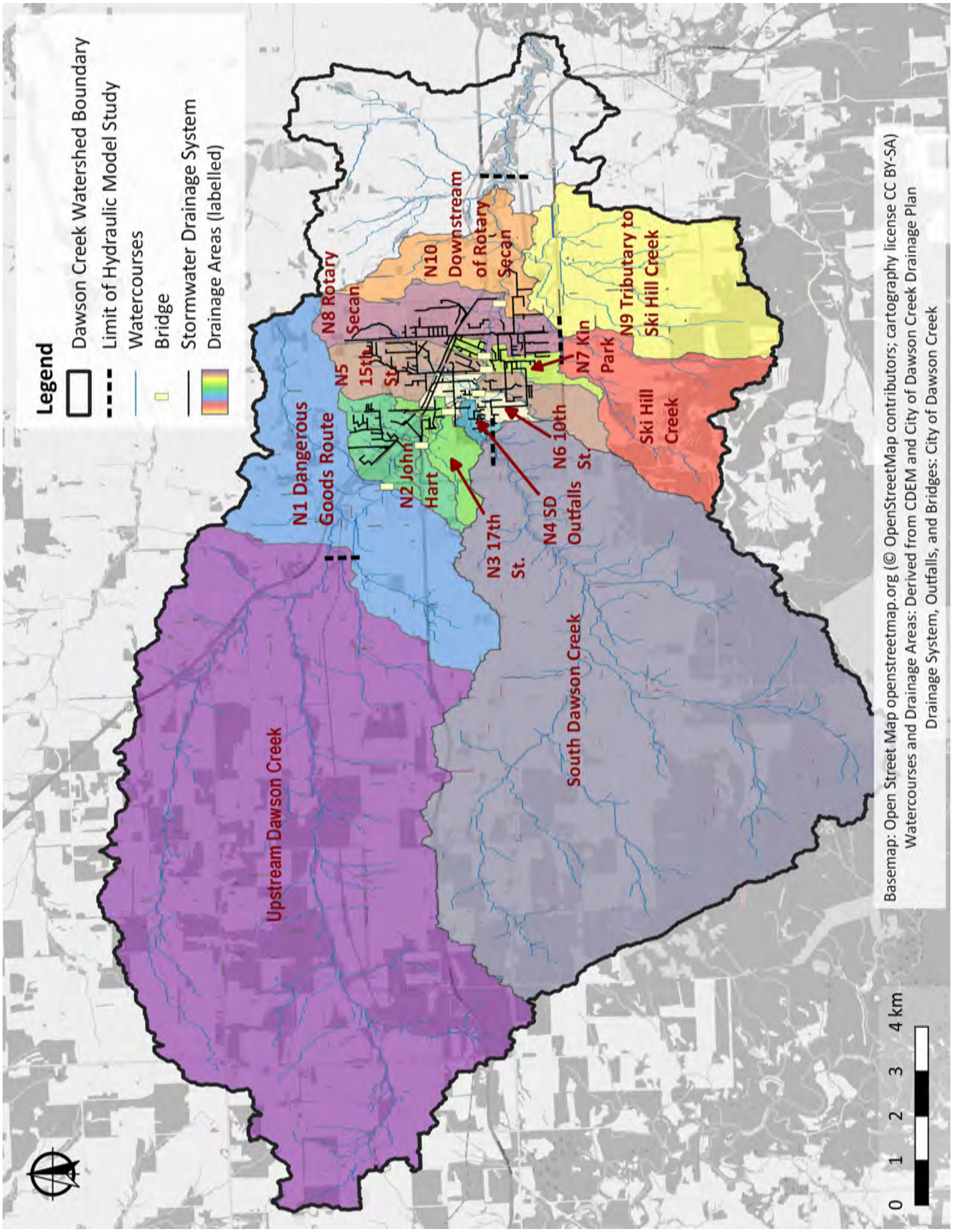

Figure 9: Drainage areas for model inflow locations, including hydraulic model boundaries for project area's main channels (Dawson Creek, South Dawson Creek, and Ski Hill Creek), as well as smaller catchments from the stormwater drainage system.

Table 3: Drainage area in square kilometres (km²) for inflows to the hydraulic model.

Name	Drainage Area (km²)	Drainage Area Type
Upstream Dawson Creek	92.2	Open channel
South Dawson Creek	85.7	Open channel
Ski Hill Creek	9.6	Open channel
N1 Dangerous Goods Rt. (DGR) Bridge	19.5	Open channel
N2 John Hart Bridge	4.0	Mixed open channel/stormwater outfalls
N3 17th St. Bridge	2.2	Mixed open channel/stormwater outfalls
N4 South Dawson Outfalls	0.5	Stormwater outfalls
N5 15th St. Bridge	1.5	Stormwater outfalls
N6 10th St. Bridge	5.5	Stormwater outfalls
N7 Kin Park Bridge	1.5	Stormwater outfalls
N8 Rotary Bridge	5.7	Stormwater outfalls
N9 Tributary to Ski Hill Creek	15.4	Open channel
N10 Downstream of Rotary Bridge	5.5	Mixed open channel/stormwater outfalls

5.3 Project Area Hydrometric Records

5.3.1 Water Survey of Canada Stations

Hydrometric data are a key input into the hydrological flood frequency analysis. Two Water Survey of Canada (WSC) station data records exist in the project area for Dawson Creek Above South Dawson Creek (WSC 07FD015) and South Dawson Creek At The Mouth (WSC 07FD016) (Table 4, Figure 10). However, both of these hydrometric stations only operated for short periods in the 1980s and 1990s, and only seasonal records were collected. Over the recorded periods, the mean daily flow was 0.29 m^3/s for Dawson Creek (above the confluence with South Dawson Creek) and 0.26 m^3/s for South Dawson Creek. The largest flows were recorded for Dawson Creek in 1983, 1987, and 1990 (Table 5). Over the historic record of 15 years, the months with the most annual peak flow events for Dawson Creek occurred in June (5), followed by April (4), May (2), July (2) and August (2).

Table 4: WSC hydrometric stations in project area.

Station Number	Station Name	Latitude	Longitude	Drainage area (km²)	Start of Record (Year)	End of Record (Year)
07FD015	DAWSON CREEK ABOVE SOUTH DAWSON CREEK	55°45’43.0¨ N	120°15’0.0¨ W	116.0	1981	1995
07FD016	SOUTH DAWSON CREEK AT THE MOUTH	55°45’23.0¨ N	120°15’0.0¨ W	85.2	1981	1985

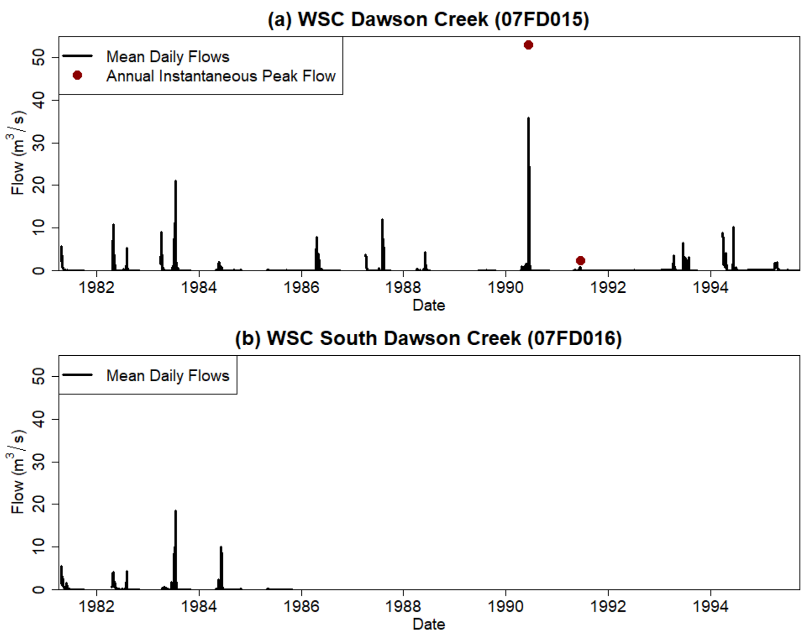

Figure 10: Daily average flow and annual instantaneous peaks (where available) in m³/s for WSC stations Dawson Creek and South Dawson Creek.

The South Dawson Creek data were considered to cover too short a range to be used for any flood frequency analysis. To prepare the Dawson Creek data for further analysis, the annual daily peak flows were converted into annual instantaneous peak flows. The annual daily peak flow indicates the maximum average daily flow in a year, while the annual instantaneous peak flow indicates the maximum flow in a year that has been recorded at the 5- to 10-minute frequency in which the flows were measured (therefore higher than the annual daily peak flow).

The annual instantaneous peak flow is usually used for flood frequency analysis. However, often instantaneous peak flows do not exist for all high flow events. This might be due to field issues during the high flow events, where the hydrometric stations might not have recorded continuously at high frequency over the event. Typically, the instantaneous peak flows also have high uncertainty and in many cases, do not meet the quality-control standards of the WSC, and are therefore not included in the published data records. Therefore, peaking factors are often used to estimate instantaneous peak flows. Peaking factors are based on the ratio of instantaneous and daily peak flow data, which are more readily available, and they are dependent on watershed-specific conditions.

Table 5: Daily and instantaneous annual peak flows for Dawson Creek and South Dawson Creek, based on historic WSC record.

Peak Flow Date	Dawson Creek Daily Annual Peak Flow (m³/s)	Dawson Creek Instantaneous Annual Peak Flow (m³/s)	South Dawson Creek Daily Peak Flow (m³/s)
1990-06-12	35.8	52.9	NA
1983-07-15	21.0	NA	18.4
1987-08-01	12.0	NA	NA

Two annual instantaneous peak flows were available for the Dawson Creek station, the 1990 instantaneous flow of 52.9 m^3/s (daily peak flow 35.8 m^3/s) and an instantaneous peak flow of 2.3 m^3/s (daily peak flow 0.7 m^3/s) from 1991. Additional unpublished field data and notes were requested from the WSC to improve the analysis, but no more data were available. Based on the two available instantaneous peak flows, peaking factors of 1.5 for the 1990 flow and 3.2 for the 1991 event were derived. The 1990 peaking factor was applied to all daily peak flows over 1 m^3/s, and the 1991 peaking factor was applied to daily peak flows less than 1 m^3/s. This method allowed conservation of the two observed instantaneous peak flows. Further, the range of the two peaking factors was too large to calculate a mean peaking factor to apply to all daily peak data. The resulting estimated annual instantaneous peak flows are shown in Figure 11.

An assumption for flood frequency analysis is that the data are stationary, that is, that no trends occurred over the period of the hydrometric record. For Dawson Creek, the Mann-Kendall test (McLeod, 2011) indicated no statistically significant trend over the time series of peak flows (p-value 0.69, for alpha = 0.05).

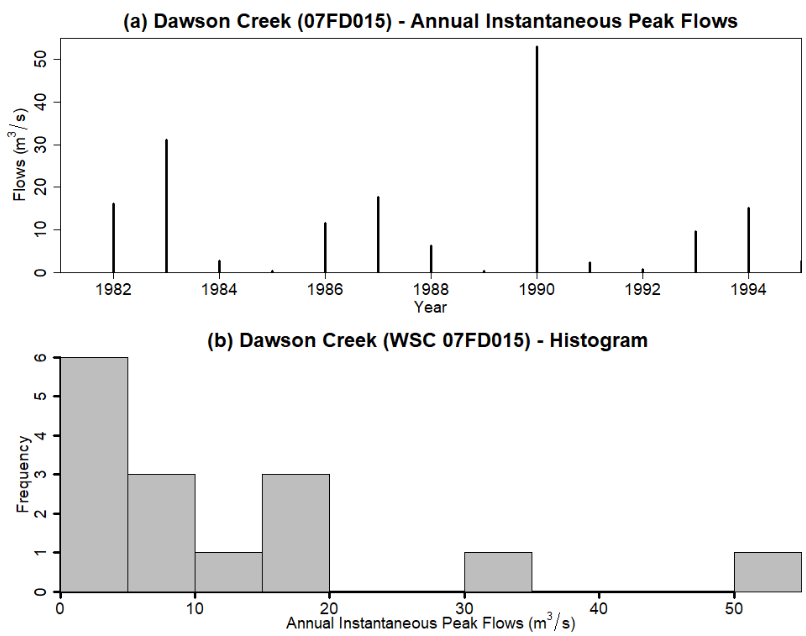

Figure 11: Dawson Creek (WSC 07FD015) estimated annual instantaneous peak flows time series (a) and histogram (b).

5.3.2 2019 Water Level Monitoring

Given the dated historic record of available flow data for Dawson Creek and South Dawson Creek, the City of Dawson Creek implemented a hydrometric monitoring program in 2019. The City installed a total of 12 hydrometric monitoring stations, where water levels were continuously recorded (Figure 12, Table 6). Challenges were encountered during the monitoring, including the occurrence of very low water levels (which stayed below the sensor level for some stations), the presence of nearby beaver dams causing low-flow pool conditions, and other field-related data losses. Figure 13 shows observed water levels for the monitoring stations. Currently, no rating curves are available to relate observed water levels to flow (i.e., discharge).

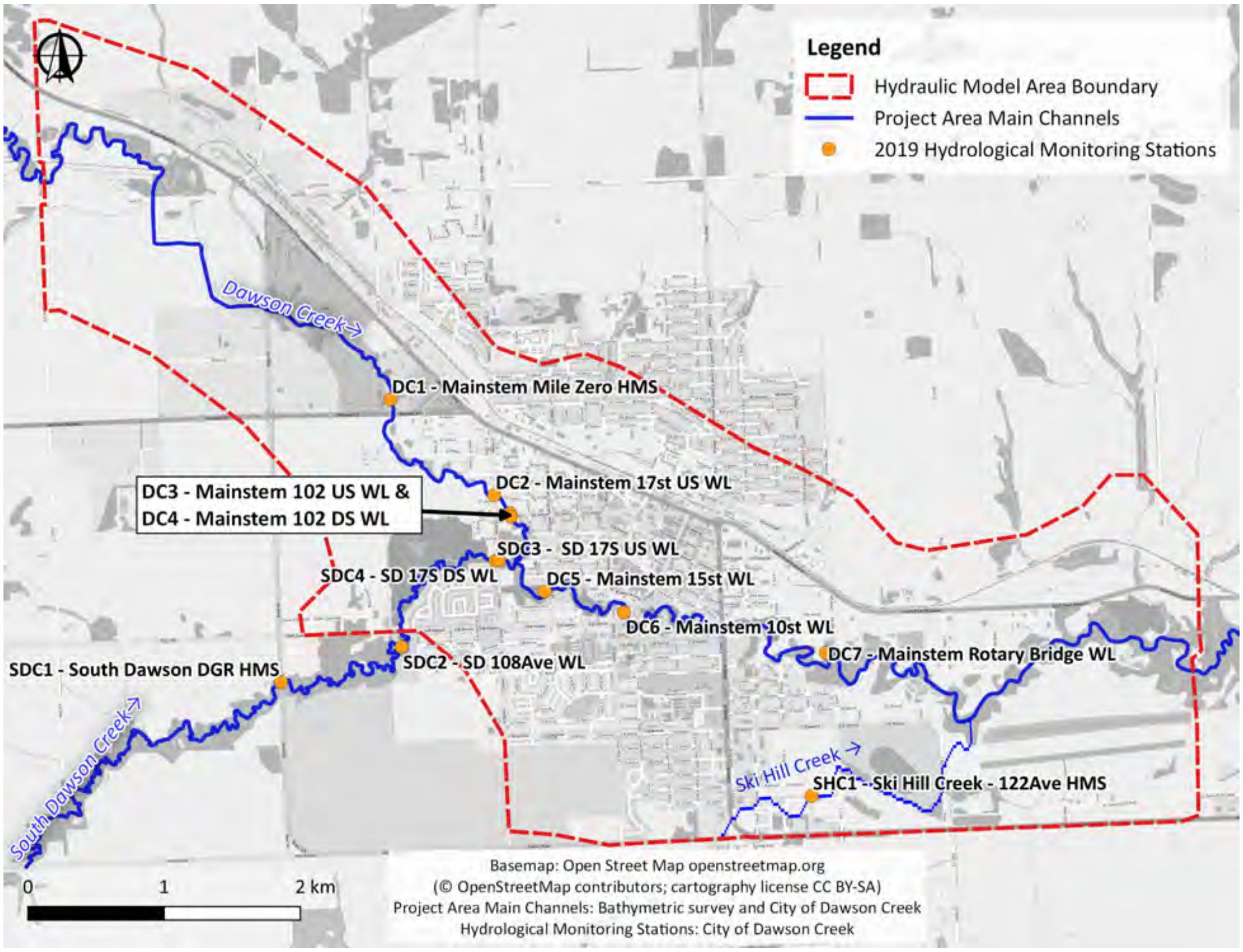

Figure 12: 2019 monitoring stations in Dawson Creek.

Table 6: 2019 monitoring stations in Dawson Creek.

ID	Name	Latitude (EPSG 26910)	Longitude (EPSG 26910)	Installation Date
DC1	Dawson Main – Mile Zero	6183593.606	671743.7395	2019-03-19 / 2019-04-04
DC2	Dawson Main – Upstream 17 St.	6182893.273	672504.1965	2019-03-20
DC3	Dawson Main – Upstream 102 Ave.	6182759.62	672623.032	2019-03-21
DC4	Dawson Main – Downstream 102 Ave.	6182733.167	672630.0872	2019-03-22
DC5	Dawson Main – 15 St.	6182210.007	672950.9034	2019-03-23
DC6	Dawson Main – 10 St.	6182036.308	673459.8925	2019-03-24
DC7	Dawson Main – Rotary Bridge	6181736.485	674939.966	2019-03-25
SCD1	South Dawson – Dangerous Goods Rt. (DGR)	6181522.764	670957.8138	2019-03-26
SCD2	South Dawson – Upstream 108 St.	6181778.739	671826.2295	2019-03-27
SCD3	South Dawson – Upstream 17 St.	6182408.407	672517.301	2019-03-28

ID	Name	Latitude (EPSG 26910)	Longitude (EPSG 26910)	Installation Date
SCD4	South Dawson – Downstream 17 St.	6182416.465	672556.4611	2019-03-29
SHC1	Ski Hill – 122 Ave.	6180684.436	674794.9987	2019-03-30

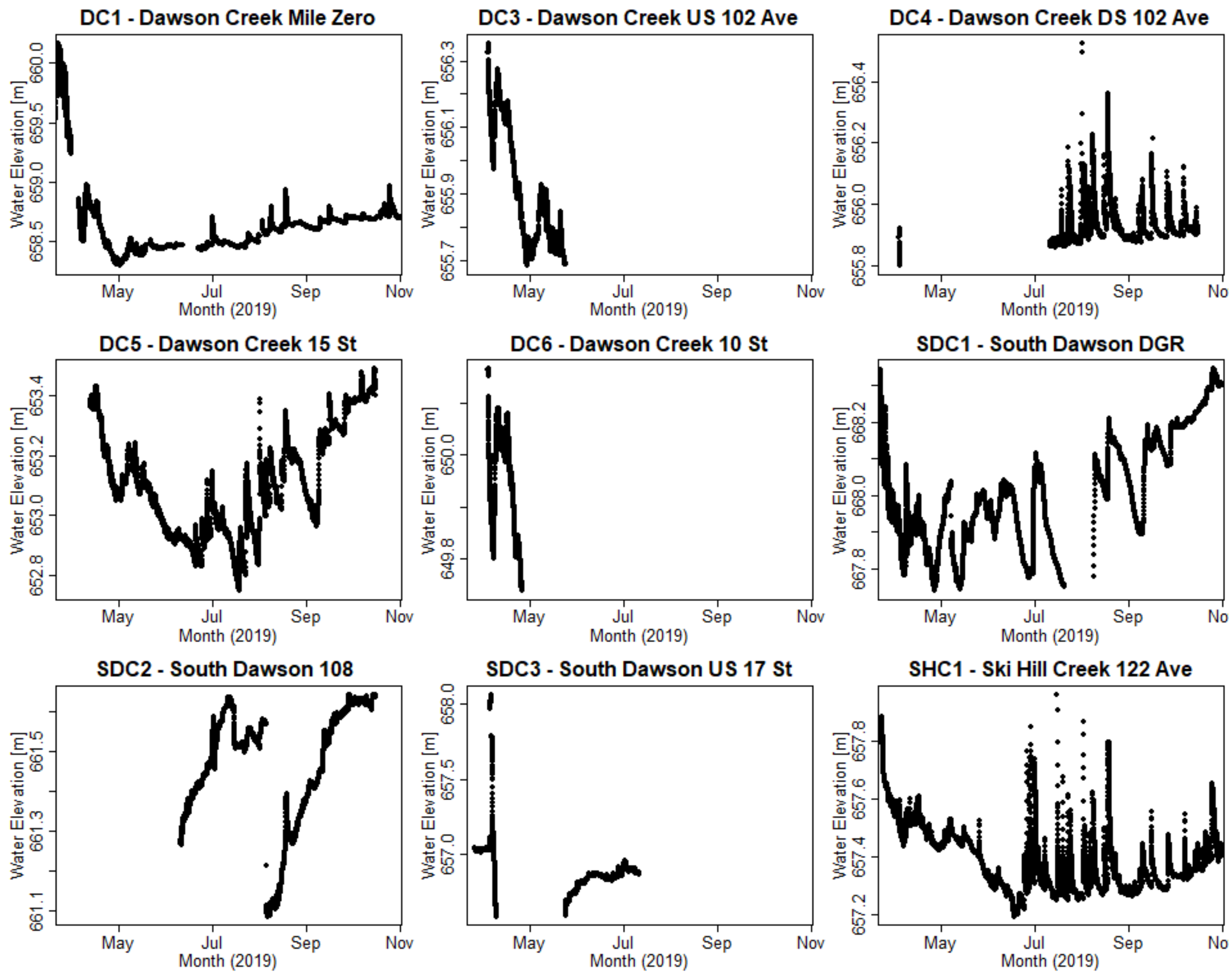

Figure 13: Water level monitoring recorded over the 2019 monitoring period. For stations D7 (Rotary Bridge) and SDC4 (Downstream 17 St.), the water elevation remained below the sensor for the duration of the monitoring.

Unfortunately, due to the issues described above, this data had limited use in the present study. However, the City should be encouraged to continue to collect hydrometric data to support future analysis. The first priority should be to continue monitoring on the Dawson Creek main channel. Of the existing station locations, the upstream monitoring location (DC1 – Dawson Creek Mile Zero) is considered the most important station, as it measures the inflows from the larger watershed into the urban core. This station also showed reliable and undisturbed data (e.g., no beaver dams) over the 2019 monitoring period. The City could also consider locating a monitoring station even further upstream on the Dawson Creek main channel in the area of the hydraulic model boundary nearby 223 Rd. Bridge. Another option on the Dawson Creek main channel would be to locate a monitoring station nearby the location of the old WSC station above the confluence with South Dawson Creek. Once hydrometric monitoring on Dawson Creek main channel has been ensured, an upstream monitoring station on South Dawson Creek could be considered (e.g., SDC2 – 108th St.; SDC1 experienced field issues due to beaver dams). Next, a hydrometric monitoring station at Ski Hill Creek (SHC 1 – Ski Hill 122nd Ave.) could be considered.

As hydrometric monitoring stations are labor- and resource-intensive to maintain, and a rating curve has to be developed for each station (which also requires substantial effort), it is recommended to concentrate efforts on 2–4 hydrometric monitoring stations and ensure high data quality for these stations. It is also recommended to conduct regular field visits and subsequent imminent checking of recorded data every two weeks to once per month to minimize data loss from field issues. Importantly, a long-term monitoring plan should be developed, as hydrologic data becomes particularly valuable over many years and decades of recording, when high and low extreme flows, as well as trends due to climate change and land use change can be observed. While hydrometric data collection does involve effort, it is an incredibly valuable dataset for the City, as it can indicate how the flows are changing over time and can provide input to flood and drought analysis and thus help to better target risk reduction measures.

5.4 Existing Condition Peak Flows

This section provides an overview of the analysis to estimate existing condition peak flows for the project area, which are the input for the hydraulic model.

5.4.1 Flood Frequency Analysis

To conduct a flood frequency analysis, a long historic record of annual peak flows is needed. However, the WSC station in Dawson Creek only operated for 15 years, which is statistically not long enough to use as input for the flood frequency analysis. Furthermore, the data are more than 25 years old, and do not represent the current hydrologic conditions in Dawson Creek. Therefore, input was needed from other hydrometric stations in the region surrounding Dawson Creek.

One method to estimate peak flows in a watershed is to do a regional flood frequency analysis. In this type of analysis, peak flows for many regional stations surrounding the area of interest are determined, and a regional flood curve is developed that relates drainage areas to peak flows. Peak flows in the study area are then estimated using the regional flood curve. However, the key here is that the regional stations are considered hydrologically representative of the area of interest. The applicability of the regional flood frequency approach for Dawson Creek was tested in detail (see Appendix B), considering 16 hydrometric WSC stations in the flat BC and Alberta Plateau region reaching eastward from Dawson Creek. However, the number of WSC stations in BC's Northeast is limited, and many stations have been discontinued. Further, it was found that most of the available WSC stations were not hydrologically representative of the project area, as they, for instance, did not experience the historically observed peak flow events of Dawson Creek (such as, in 1990, 2001, or 2016), or substantially underestimated peak flows for the project area. This might be due to the fact that many of these stations are up to 100 km from the project area and further from the mountains, and typically have flatter topography than Dawson Creek. Inclusion of these stations in a regional flood frequency analysis would have led to an underestimation of peak flows in the project area.

Similar challenges with regional hydrometric stations were observed by NHC in their 2017 study, and they excluded most regional stations, as they were not considered hydrologically representative (see Section 5.1; NHC, 2017). The development of regional flood curves was also tested based on only the closest hydrometric stations (the Kiskatinaw River near Farmington WSC station (07FD001), Pouce Coupé WSC station (07FD007), and the Dawson Creek WSC station (07FD015). However, with such a small number of stations, too much weight was on the Dawson Creek WSC station data, which, as previously discussed, statistically do not cover a long enough time period for a flood frequency analysis, and are also more than 25 years old. For these reasons, it was not statistically and hydrologically satisfactory to use a regional flood frequency analysis approach to determine the peak flows for this study, and another approach was needed.

Therefore, an approach was used where peak flows are directly inferred from a nearby station. Both the Kiskatinaw River near Farmington WSC station (07FD001) and the Pouce Coupé WSC station (07FD007) were prime candidates for this analysis, as the Kiskatinaw River watershed is located next to the Dawson Creek watershed, and Dawson Creek is a tributary to the Pouce Coupé River. Both stations also have long historical records (from 1966 to 2019 for the Kiskatinaw River, and from 1977 to 2019 for the Pouce Coupé River). Details on the Kiskatinaw River near Farmington WSC station (07FD001) and the Pouce Coupé WSC station (07FD007) hydrometric data and processing are provided in Appendix B.

To evaluate if the Kiskatinaw River and Pouce Coupé River were indeed hydrologically similar to Dawson Creek, the correlation coefficients were assessed of the annual peak flows of Dawson Creek with these two stations over the period where data existed for Dawson Creek (i.e., from 1981 to 1995). The Kiskatinaw River had a very good relationship with Dawson Creek, with a coefficient of determination of $R^2 = 0.8$, and a Pearson product-moment correlation coefficient of $r = 0.89$. The Pouce Coupé dataset had a data gap from 1990 to 1995, therefore only overlapped with the Dawson Creek data from 1981 to 1989. The correlation of annual peak flows over this period was not as good as for the Kiskatinaw, with $R^2 = 0.69$ and $r = 0.83$. Considering the better correlation for the Kiskatinaw, the longer data overlap (which is important for determination of a parameter), and given that the Kiskatinaw watershed directly borders the Dawson Creek watershed and is characterized by similar topography, further analysis was pursued using the Kiskatinaw WSC station.

A common way to estimate peak flows of an ungauged location (such as Dawson Creek) from a gauged location (such as the Kiskatinaw) is to weigh the ratio of the drainage areas, using the equation shown below (USDA, 2008):

$$Q_{ungauged} = Q_{gauged} \left(\frac{A_{ungauged}}{A_{gauged}}\right)^{x} \qquad \text{Equation 1}$$

where $Q_{ungauged}$ (m^3/s) is the peak flow of the ungauged site, Q_{gauged} (m^3/s) is the peak flow of the gauged site, $A_{ungauged}$ (km^2) is the drainage area of the ungauged site, A_{gauged} (km^2) is the drainage area of the gauged site, and the exponent x (dimensionless) is a slope exponent that relates flow to area. The exponent x is sometimes given for specific hydrographic regions (for instance, in the US). However, no exponent was available for the region of Dawson Creek, and further, the historical record of Dawson Creek could be used to estimate an exponent specifically for the characteristics of Dawson Creek.

The exponent x was therefore determined by solving Equation 1 for x, and inserting the instantaneous annual peak flows for the Kiskatinaw and Dawson Creek for each year from 1981 to 1995. The mean of x was then calculated for the 5 biggest peak flows (the high extreme flows), resulting in x = 0.89. Next, the flood frequency analysis was conducted for the Kiskatinaw instantaneous annual peak flow record from 1996 to 2019 (see Appendix B for details on the Kiskatinaw peak flow time series). Using the method of L-Moments, a frequency distribution was fitted to the Kiskatinaw instantaneous annual peak flow record (Figure 14). The frequency distribution of best fit was the Generalized Extreme Value (GEV) distribution, which is a distribution also recommended in the *Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation* guideline (Natural Resources Canada, 2019b). The peak flows were then calculated for each of the AEPs of interest for the Kiskatinaw River (see Appendix B). The flood frequency analysis was conducted using the R packages "extremeStat" (Boessenkool, 2017) and "lmomco" (Asquith, 2011; Asquith, 2018), processing of the WSC data was conducted using "tidyhydat" (Albers, 2017) and "FlowScreen" (Dierauer and Whitfield, 2019).

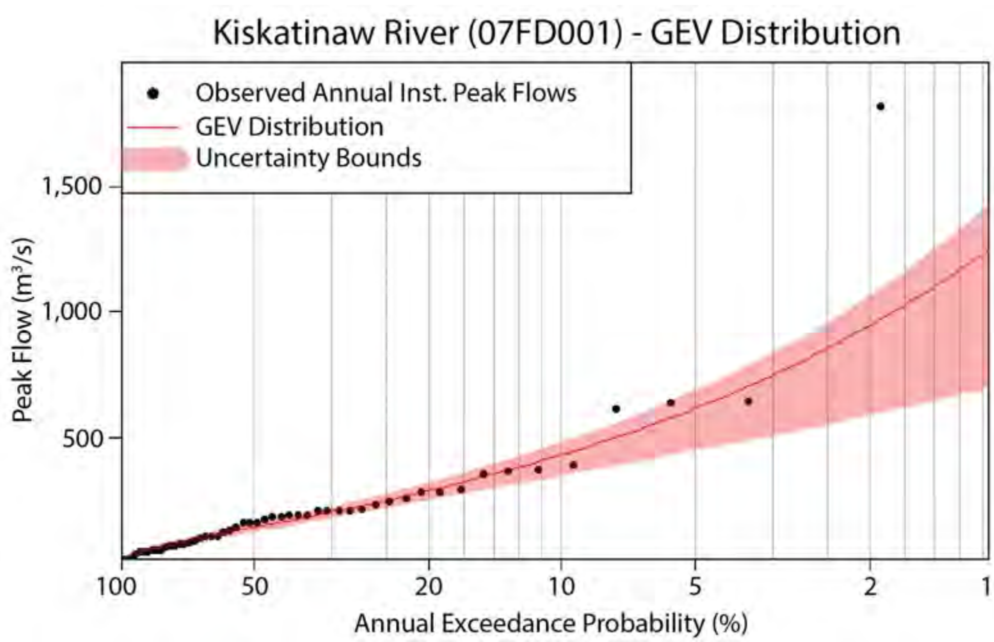

Figure 14: GEV distribution fitted to the Kiskatinaw River (07FD001) annual instantaneous peak flows via the methods of L-Moments. Uncertainty bounds are represented by red shading.

Based on the instantaneous peak flows estimated for the Kiskatinaw River, the Kiskatinaw River drainage area of 3,630 km^2, the exponent x of 0.89, and drainage areas delineated in Section 5.2, the peak flows were estimated for each of the model inflows for the project area, using Equation 1 (Table 7, Table 8). Equations for each AEP are provided in Appendix B.

The largest peak flows are estimated for Upstream Dawson Creek and South Dawson Creek, followed by N1 Dangerous Goods Route, N9 Tributary to Ski Hill Creek, as well as Ski Hill Creek. The remainder of the hydraulic model inflows, most of which are part of the stormwater drainage system, are relatively small in comparison.

Table 7: Annual exceedance probability (AEP) peak flows in cubic metres per second (m^3/s) for model inflows (AA).

AEP (%)	Upstream Dawson Creek (m^3/s)	South Dawson Creek (m^3/s)	Ski Hill Creek (m^3/s)	N1 Dangerous Goods Rt. (m^3/s)	N2 John Hart Bridge (m^3/s)	N3 17th St. Bridge (m^3/s)
50	6	5	0.7	1.4	0.3	0.2
20	11	10	1.5	2.8	0.7	0.4
10	17	16	2.2	4.2	1.0	0.6
2	36	34	4.9	9.1	2.2	1.3
1	49	46	6.6	12.4	3.0	1.8
0.5	67	62	8.9	16.7	4.1	2.4
0.2	98	92	13.1	24.6	6.0	3.5

Table 8: Annual exceedance probability (AEP) peak flows in cubic metres per second (m^3/s) for model inflows (B).

AEP (%)	N4 South Dawson Outfalls (m^3/s)	N5 15th St. Bridge (m^3/s)	N6 10th St. Bridge (m^3/s)	N7 Kin Park Bridge (m^3/s)	N8 Rotary Bridge (m^3/s)	N9 Tributary to Ski Hill Creek (m^3/s)	N10 Downstream of Rotary (m^3/s)
50	0.1	0.1	0.5	0.1	0.5	1.1	0.5
20	0.1	0.3	0.9	0.3	0.9	2.3	0.9
10	0.2	0.4	1.4	0.4	1.4	3.4	1.4
2	0.4	0.9	3.0	0.9	3.1	7.4	3.0
1	0.5	1.2	4.0	1.3	4.2	10.1	4.0
0.5	0.7	1.7	5.4	1.7	5.7	13.6	5.4
0.2	1.0	2.5	8.0	2.5	8.3	20.0	8.0

For the Upstream Dawson Creek inflow (i.e., the main inflow into the hydraulic model), a 0.5% AEP flow of 67 m^3/s was estimated. This is within a similar range as was estimated for the same location by Urban Systems (71 m^3/s) and NHC (65 m^3/s), when applying the regional flood curve equations provided in the respective reports (NHC, 2017; Urban Systems, 2017a). However, it is important to consider that there is substantial uncertainty related with the peak flow estimates, and depending on the methodology and regional hydrometric stations used, peak flows can vary. This is indicated in Figure 15, which shows the final peak flows for the Upstream Dawson Creek model inflow, as well as the maximum and minimum estimates obtained during the regional flood frequency analysis (details on the regional flood frequency approach are in Appendix B). Uncertainty increases substantially for the larger peak flows (lower likelihood events).

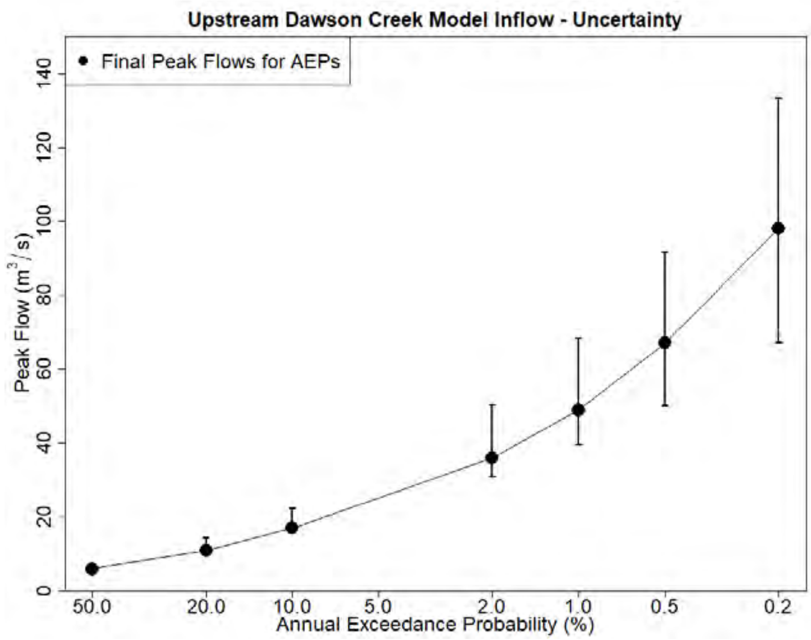

Figure 15: Uncertainty bounds for Upstream Dawson Creek model inflow, indicating the final AEP peak flows as well as the maximum and minimum estimates obtained in regional flood frequency analysis.

The uncertainty bounds, and the potential impact of these on the hydraulic model and flood mapping, are considered later in this report as part of the sensitivity analyses conducted for the hydraulic model.

5.4.2 Hydrographs

The hydraulic model was run for unsteady flow conditions (Section 6), which means that not just the instantaneous peak flow as calculated above is applied to drive the hydraulic model. Instead, a hydrograph is applied for each sub-catchment, where the inflow changes with each time step, typically over several days. This is a more realistic approach to hydraulic modelling, as in reality, river levels rise and fall over several days. Further, this approach provides a more realistic estimate of the total volume of water; this is important in small systems where floodplain storage affects overall system hydraulics. Typically, the model hydrograph is based on a historic hydrograph observed in the watershed, and then scaled to reflect the peak flow estimates.

For Dawson Creek, the biggest historic flow event was recorded in June 1990 (Figure 16). The hydrograph of this event (from 5 June to 19 June 1990) was converted to a unitless hydrograph, where the peak value equalled 1. Considering the limited data availability of hydrographs for other locations within the Dawson Creek watershed, as well as the small overall extents of the watershed, it was assumed that this hydrograph can approximate all inflows to the hydraulic model.

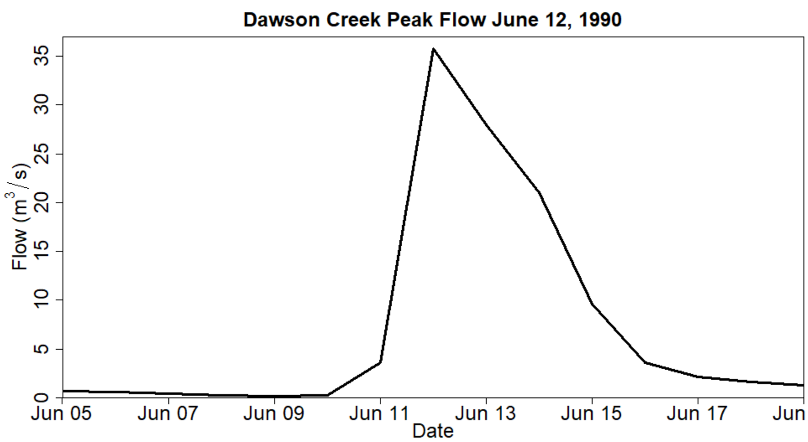

Figure 16: Observed 1990 peak flow at Dawson Creek (WSC 07FD015).

For the 5 locations with larger peak flows (i.e., the 3 model boundaries (Upstream Dawson Creek, South Dawson Creek, Ski Hill Creek) as well as the tributary inflows N1 Dangerous Goods Route and N9 Tributary to Ski Hill Creek), unsteady hydrographs were produced for hydraulic model input by scaling the unitless hydrograph to the respective peak flows for the range of AEP scenarios (Figure 17). For these five inflows, the same hydrograph timing was assumed, as the overall watershed extents are relatively small, which allows the assumption of similar local weather patterns, and the two main inflows (Upstream Dawson Creek and South Dawson Creek) have a similar drainage area, topography and land cover, such allowing the assumption that generated run-off would arrive at the model inflow with similar timing. Further, no prior data existed to inform hydrograph timing for inflow locations, and setting up a catchment model to estimate inflow timing was not possible within the time frame of the project.

For all other smaller inflows, stationary flow was assumed, and the average flow was calculated over the peak of the hydrograph (i.e., over the period when flows were higher than baseflows).

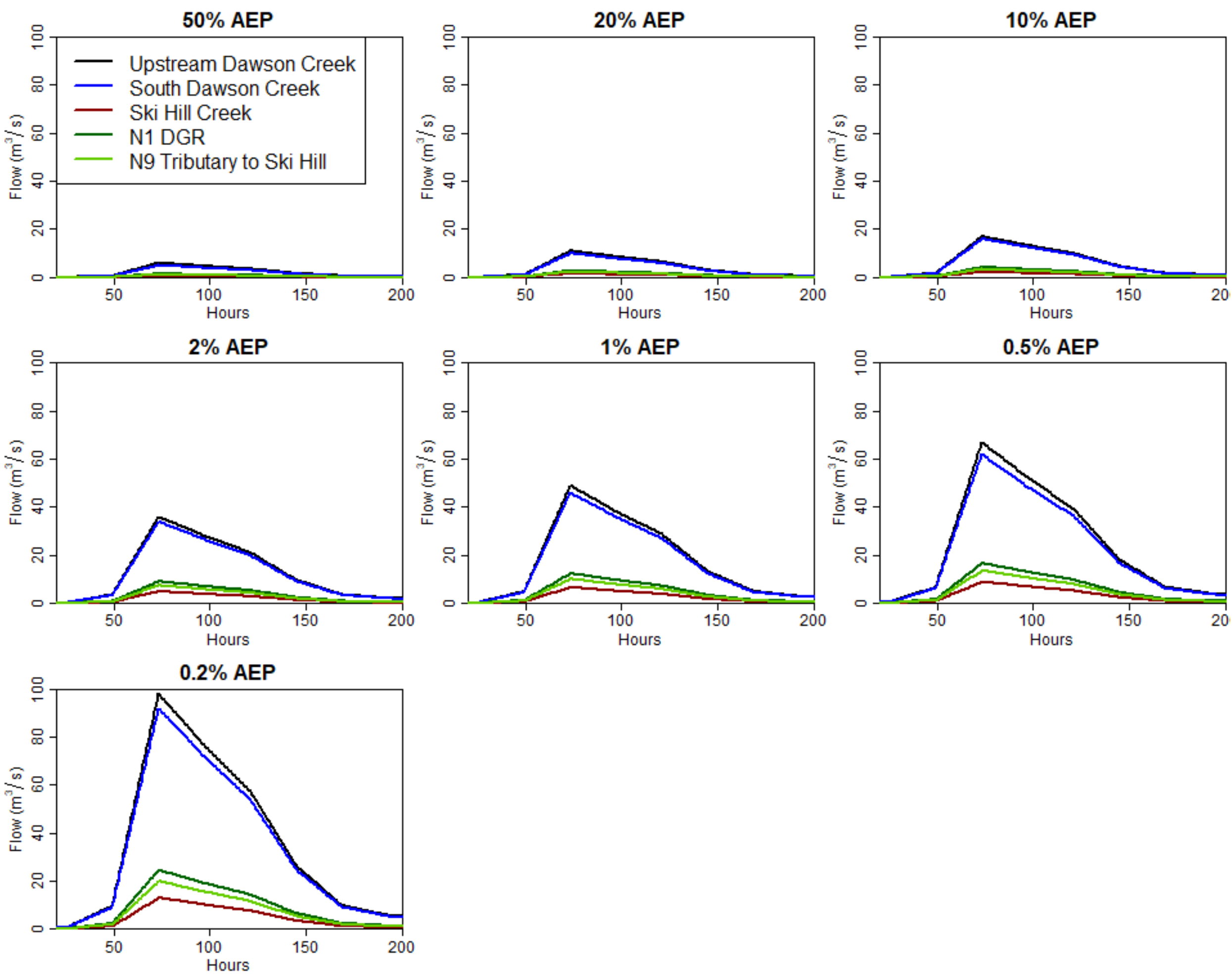

Figure 17: Hydrographs for different AEP scenarios.

5.4.3 2016 Flood Event

We also estimated flows for the 2016 flood event in Dawson Creek to allow modelling of this event in the hydraulic model (Section 6.3). Urban Systems had estimated peak flows for the June 2016 event for Dawson Creek (before the confluence with South Dawson Creek) and for South Dawson Creek (before the confluence with Dawson Creek) (see Table 9; Urban Systems, 2016, 2017a). The 2016 peak flow estimates were based on the average of the Urban Systems estimate for Dawson Creek. Then, the average of the South Dawson Creek estimated flow was used to evaluate our approach.

Table 9: Flows for the June 2016 flood event for Dawson Creek and South Dawson Creek, estimated by Urban Systems (2016, 2017a).

Location	Flows estimated by Urban Systems (2016, 2017a)	
	Range (m^3/s)	Average (m^3/s)
Dawson Creek (above the confluence with South Dawson); drainage area 116 km^2)	48 – 59	53.5
South Dawson Creek (above the confluence with Dawson Creek; drainage area 86 km^2)	38 – 46	42

The same approach was used for estimating peak flows for all the inflow locations (as discussed in Section 5.4.1), solved for an estimate of the Kiskatinaw flow (here used as an equation constant) using the Dawson Creek 2016 estimate and drainage area, and then the 2016 peak flow was estimated for all inflow locations (Table 10). The total estimate[10] for South Dawson Creek (at the confluence with Dawson Creek) is similar to what Urban Systems had reported for South Dawson Creek at the confluence. This provided confidence in the estimation approach in this analysis.

The frequency analysis for this study indicated that the June 2016 flood event had an approximate 1.3% AEP. This estimate was based on the available data and methods, and therefore, comes with some uncertainty. The results indicate that, in the existing conditions, every year there is a 1.3% chance of a flood event of similar (or larger) size to occur, which highlights the importance for flood risk reduction measures. It is also important to remember that, while such a big flood event has only recently occurred, it does not mean it will now not occur again for many years, but that each year, there is an (albeit relatively small) chance that it might occur again.

For hydraulic modelling of the event, an event hydrograph was needed. However, no hydrograph was available for the 2016 flood event, therefore the same hydrograph generation process was used as described in Section 5.4.2, which may have led to some differences between the modelled and observed 2016 flood extents. The limitations of this are discussed in more detail in Section 6.3.

Table 10: Estimated peak flows for June 2016 flood event.

Name	Estimated Peak Flows for June 2016 Flood Event with an approximate 1.3% AEP (m^3/s)
Upstream Dawson Creek	44.0
South Dawson Creek	41.0
Ski Hill Creek	6.0
N1 Dangerous Goods Rt. (DGR) Bridge	10.9
N2 John Hart Bridge	2.7
N3 17th St. Bridge	1.6
N4 South Dawson Outfalls	0.5
N5 15th St. Bridge	1.1
N6 10th St. Bridge	3.6
N7 Kin Park Bridge	1.1
N8 Rotary Seacan Bridge	3.7
N9 Tributary to Ski Hill Creek	8.9
N10 Downstream of Rotary Seacan Bridge	3.6

[10] The flow estimated by the current study for South Dawson Creek (above the confluence with Dawson Creek) was 41.5 m^3/s, and was calculated as the sum of the South Dawson Creek flow at the hydraulic model boundary (41.0 m^3/s) and the inflow of N4 South Dawson Outfalls inflow (0.5 m^3/s).

5.5 Peak Flows Under Climate Change

The climate is changing, and the consequences of this will be felt in BC's Northeast in terms of changes in air temperatures, rainfall, and snowpack (FBC, 2019). These changes will, in turn, likely have consequences on flooding in the region. This section assesses potential changes to peak flows in Dawson Creek due to climate change. The results in this section refer to the internationally recognized "business as usual" greenhouse gas emission scenario—the Representative Concentration Pathway (RCP) 8.5 (see the Climate Change Primer in Appendix B for more information on climate change modelling). This is a greenhouse gas emission scenario chosen by many jurisdictions in BC and across the world as a planning scenario. Results presented in this section are based on the newest analysis from the Pacific Climate Impacts Consortium (PCIC) (FBC, 2019).

5.5.1 Temperature, Precipitation, and Snowpack Change in the Northeast

Climate change modelling results indicate increases in air temperature throughout the Northeast, in particular in the lowlands (including the City of Dawson Creek), where the number of days above 25°C will increase by almost 4 times from the past to the 2080s (FBC, 2019). Winter temperatures are also projected to warm, and by the 2080s, "January temperatures will feel like March temperatures of the past, with warmer nights and fewer frost days" (FBC, 2019).

Precipitation is also projected to increase, in particular during the spring and fall. Furthermore, precipitation intensities will increase. An indicator of extreme precipitation (the 95th percentile wettest days[11]) is projected to increase by 35% in the 2050s and by 51% in the 2080s in comparison to the past in the Northeast lowlands (FBC, 2019). This is relevant for flooding, as intense precipitation can cause flood events (as occurred during the 2016 flood).

Along with warmer temperatures, the snowpack is also projected to decrease substantially in the Northeast, with greater relative decrease in the lowlands than in the mountains (FBC, 2019). Specifically, the snowpack[12] for the Kiskatinaw and Pouce Coupé watersheds is projected to decrease by 52% by the 2050s and by 76–79% by the 2080s (for a snowpack estimated for April 1). The snowpack estimated for May 1 shows an even greater decrease, with a reduction of 84–87% by the 2050s, and of 84–97% by the 2080s. These reductions in snowpack will also have consequences for flooding in Dawson Creek.

5.5.2 Hydrological Modelling of Climate Change in the Region

Projections of climate change typically provide information on changes in air temperature or precipitation. However, to translate these meteorological changes to consequences on streamflows, a hydrological model is needed. A hydrological model is a software tool that describes all water fluxes and storage components in a watershed, including precipitation, snowpack accumulation and melt, evapotranspiration, infiltration into the soil, as well as surface runoff to a watercourse. A hydrological

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[11] The 95th percentile wettest days describes the rainfall amount that occurs on the wettest days of the year, when the precipitation exceeds the annual 95th percentile of wet days during the historic baseline period.

[12] Changes in snowpack are reported in an indicator called snow water equivalent (SWE), which measures how much water is present within a snowpack. The April 1 and May 1 SWE describes the amount of water in the snowpack on that date.

model is set up for a specific region or watershed, and calibrated to historical records of streamflow (i.e., model parameters are changed so that the observed and modelled records are as similar as possible).

PCIC has set up a regional hydrological model for the Northeast, which they used to explore climate change consequences on streamflow (FBC, 2019). They used the Variable Infiltration Capacity (VIC-GL) hydrological model with a spatial resolution of approximately 30 km^2 (PCIC, 2020a). This model was driven by 6 downscaled general circulation models (GCMs)[13] (see Appendix B).

Considering the spatial resolution of the hydrological model, no results were available for the small Dawson Creek watershed specifically, but routed discharge was available for the Kiskatinaw and Pouce Coupé WSC station locations. PCIC provided these results for further analysis; however, it is important to highlight here that hydrological model calibration results for these two locations were not as good as the overall results[14]. This might be due to the model set-up or the calibration approach not capturing the lowlands region well, where there are more mid-winter snow melting events than in the mountainous regions in other parts of BC[1414]. The hydrological model may be improved by PCIC (in cooperation with the City of Dawson Creek) in the future, and the results presented here should be considered preliminary.

5.5.3 Peak Flows Under Climate Change

As no routed discharge was available for Dawson Creek, to estimate peak flows under climate change an approach was used that was similar to the one used to estimate existing condition peak flows. Peak flows were inferred based on the Kiskatinaw River. First, the percentage change between the modelled past and 3 modelled future time periods[15] was calculated. The percentage change between the modelled past and future was applied to the existing condition peak flows that were determined based on the observed historic flow record. By determining the percentage change between the modelled past and future, some of the inherent model biases can be reduced, and it is also general best practice in climate change analysis to compare the modelled future to the modelled past.

Climate change impacts were determined for 3 future time periods in comparison to the past. The past period was chosen as 1966 to 2019, which reflects the length of observed records at the Kiskatinaw River WSC station. The 3 future periods included:

- **The 2030s**: from year 2021 to year 2050 (chosen as the next 30 years).
- **The 2050s**: from year 2041 to year 2070 (chosen to be consistent with the *Climate Projections for the Northeast BC Region* report; FBC, 2019).

[13] A general circulation model (GCM) is a global climate model that represents atmosphere, ocean, and Earth system interactions. It typically has a low spatial resolution (as it spans the whole Earth), and needs to be adjusted ("downscaled") to be representative at the regional scale. See the climate change primer in Appendix B for more information on how climate change modelling is done.
[14] Personal communication with Arelia Schoeneberg, Hydrologist, Pacific Climate Impacts Consortium (PCIC). August 2019.
[15] PCIC also ran the hydrological model for each GCM for the past, which allowed the comparison between modelled and observed past streamflow.

- **The 2080s**: from year 2071 to year 2100 (chosen to be consistent with the *Climate Projections for the Northeast BC Region* report; (FBC, 2019).

The projections for the 2050s can guide mid-term planning and infrastructure decisions, while the 2080s projections can guide more long-term planning.

Over each of these 4 time periods, a flood frequency analysis was conducted for each of the 6 GCMs. The annual daily peak flow was determined for each time period and GCM. As only daily flows and no instantaneous peak flows were available, it was assumed that the percentage change for instantaneous peak flows between the past and the future would be the same as for daily peak flows. The GEV frequency distribution was then fitted to the annual peak flow time series (for consistency across time periods and GCMs, the GEV frequency distribution was applied to all datasets). Next, the peak flows were determined for the AEPs of interest for each GCM and the percentage change was calculated for the future time periods in comparison to the modelled past.

Lastly, for each time period, the average percentage change was determined across all 6 GCMs, as well as the 10th and 90th percentile of the model ensemble (Table 11). Results in Table 11 indicate large ranges of percentage change between the 6 GCMs. The 6 GCMs had been selected by PCIC to represent a wide range of future climate extremes (and they were all part of 12 GCMs that PCIC had previously selected to well represent climate conditions in BC) (PCIC, 2020b). The percentage change for the 2030s compared to the past is relatively minimal and can probably be considered as being within the general uncertainty of the analysis. Much more substantial change is projected for the 2050s, when between a 13% and a 29% increase in peak flows is projected in comparison to the past, which would increase flood hazard considerably.

In the 2080s however, substantial change is projected dominantly for the more frequent AEPs (for instance, the 50% AEP has a projected increase of 21%), while the rarer AEPs have very small projected changes in comparison to the past—similar results have also been reported by PCIC in the *Climate Projections for the BC Northeast Region* report (FBC, 2019). This might be due to a fine threshold between increasing rainfall intensities and a much-decreased snowpack with an earlier freshet. The shift to warmer temperatures will lead to more precipitation falling as rain instead of snow, and projections for 2080 indicate for the Kiskatinaw a reduction in the May 1 snowpack of 92% (FBC, 2019). This would lead to a reduced freshet in the spring. While many of the historic events were caused by intense rainfall (NHC, 2017; Sharma, 2019), many have also occurred during the spring, when flows were already high due to snowmelt (freshet). Thus, the substantial reduction in snowpack may explain the small change for rare AEPs in the 2080s. However, it is also important to highlight the large variability between GCMs. While some GCMs projected a decrease in peak flows for the 2080s, other GCMs projected substantial increases, with a 90th percentile of up to +22%. Considering the wide range of GCM projections and the challenges of the hydrological model in representing the Kiskatinaw River flows, these results should be considered preliminary and should be updated in the future, when new hydrological modelling and potentially a more detailed assessment of GCMs is available.

Table 11: Percentage change for the future time periods in comparison to the modelled past, indicating average and range of the 6 GCMs.

AEP (%)	% Change 2030s for Kiskatinaw average (Range)	% Change 2050s for Kiskatinaw average (Range)	% Change 2080s for Kiskatinaw average (Range)
50	+3 (-6 to +15)	+13 (+1 to +26)	+21 (+4 to +41)
20	0 (-8 to +10)	+14 (+6 to +22)	+15 (0 to +46)
10	-2 (-9 to +6)	+15 (+9 to +23)	+11 (-4 to +33)
2	-7 (-15 to +4)	+18 (+1 to +37)	+5 (-13 to +26)
1	-8 (-19 to +3)	+21 (-4 to +48)	+2 (-16 to +23)
0.5	-10 (-22 to +6)	+24 (-8 to +60)	0 (-19 to +21)
0.2	-11 (-27 to +10)	+29 (-14 to +77)	-3 (-23 to +22)

Next, the percentage change for each AEP and time period (Table 11) was applied to the historical peak flows of the Kiskatinaw River, and then the projected Kiskatinaw River flows were related to Dawson Creek inflows via the drainage area relation (Equation 1) discussed in Section 5.4.1. This resulted in the peak flows for the Upstream Dawson Creek model boundary represented in Table 12 (and provided for other hydraulic model inflow locations in Appendix B). Hydrographs were developed as described in Section 5.4.2, by scaling the unitless hydrograph to the peak flows for each AEP and time period for each of the 13 inflow locations.

Table 12: Peak flows for different AEPs for the past, as well as for 3 future time periods for the Upstream Dawson Creek Model Boundary.

AEP (%)	Upstream Dawson Creek Peak Flows			
	Past (1966 – 2019) (m^3/s)	2030s (m^3/s)	2050s (m^3/s)	2080s (m^3/s)
50	6	6	6	7
20	11	11	13	13
10	17	16	19	18
2	36	34	43	38
1	49	45	60	50
0.5	67	60	83	67
0.2	98	87	126	95

5.6 Limitations

The flood frequency analysis for the existing conditions and under climate change has a number of limitations to be aware of. The first and foremost limitation to the analysis was related to the lack of local hydrometric data. The dated and short range of historic hydrometric records for Dawson Creek was not sufficient for use in a flood frequency analysis. Therefore, inference from a nearby regional station had to be made to estimate peak flows. Overall, active hydrometric stations in BC's Northeast were limited, and not many stations were hydrologically representative of Dawson Creek.

Further, hydrometric records rarely span a long enough range to provide information on rare extreme peak flows. Thus, flood frequency analysis in itself always has inherent uncertainty, and frequency distributions have to be extrapolated to estimate peak flows for rare events. Another consequence of the limited hydrometric data was that only one historic peak flow hydrograph was available.

Lastly, climate change impact analysis always comes with many uncertainties, ranging from the greenhouse gas emission scenario to the modelling approach. Further, the climate change results were based on PCIC hydrological modelling results that are considered preliminary for the Kiskatinaw River, and the climate change analysis should be updated in the future when better modelling becomes available. Furthermore, for the purpose of the analysis, stationarity was assumed over the 30-year future time periods, and with the updated hydrological modelling data, an analysis considering the effects of non-stationarity should be conducted.

Despite these limitations, the hydrological analysis provided a detailed and robust analysis of peak flows for Dawson Creek, by inferring peak flows based on the good relation between observed peak flows in Dawson Creek and the Kiskatinaw River, and provided an indication of what range of peak flows may be expected under climate change.

6 Hydraulic Model

Computational hydraulic models are tools that can be used to understand flow patterns across various past and projected-future events, and that can also be used to test the impact of changes to the system. A computational model was developed to support the development of flood maps. The model was also used to evaluate flood mitigation options.

The first step in a modelling project is to develop the basis of a hydraulic model. This generally includes creating a DEM, developing a model mesh that suits the landscape, and incorporating structural components such as bridges, culverts, and dams. The boundary conditions then need to be defined. This section provides technical information on this process as well as information to understand the uses and limitations of the hydraulic model. For more details about the model please refer to Appendix C.

6.1 Software Selection

A range of software is available for hydraulic models, each of which has strengths and shortcomings. Prior to developing a hydraulic model, the software that suits local characteristics and meets the needs of the end user must be selected.

A review of relevant modelling software was conducted based on the project's hydraulic modelling requirements. The criteria considered technical suitability, as well as important practical concerns related to sustainability and user experience. The software selection process is detailed in a memo attached to Appendix C. Through the selection process, the US Army Corps of Engineers Hydrologic Engineering Center River Analysis System (USACE HEC-RAS model, version 5.0.7) was chosen.

The two-dimensional (2D) component of the HEC-RAS software is relatively newly developed. It expands upon the HEC-RAS 1D software, one of the most referenced programs in this discipline. The development of the 1D software has been continuous since 1995, when the first model version was released. HEC-RAS 2D offers the additional options for hydrodynamic flow or coupled 1D-2D solutions. This software was selected because it allows more flexibility in the future use of the model. For example, the interface allows for modifications, such as the addition of culverts, to be made more easily than other software. It offers an improved user-friendly interface and online user support. Further, it is widely used by practitioners in BC, and therefore the City should easily find consultants to adjust parameters in future.

6.2 Model Set-Up

The following provides a brief summary of the steps and components of the hydraulic model.

6.2.1 Model Boundaries

The hydraulic model includes the City of Dawson Creek, Dawson Creek, and the main tributaries. The extent was determined based on identification of the project area's watercourses, available channel bottom or bathymetric data, and client requirements. The extent is presented in Figure 18. The project area main channels, are described below:

- **Dawson Creek.** The upstream extent is the crossing at 223 Rd., approximately 200 m north of Reasbeck Rd. The downstream extent is east of the airport, approximately 400 m south of 213 Rd.

- **South Dawson Creek.** The upstream extent is in the vicinity of the Dawson Creek confluence, near 108th Ave. and 20th St.
- **Ski Hill Creek.** The upstream extent is at Highway 2 and 8th St.

In addition to the project area's main channels, 10 minor tributaries and their drainage areas were included as detailed in the hydrologic analysis (Section 5), and also shown in Figure 18.

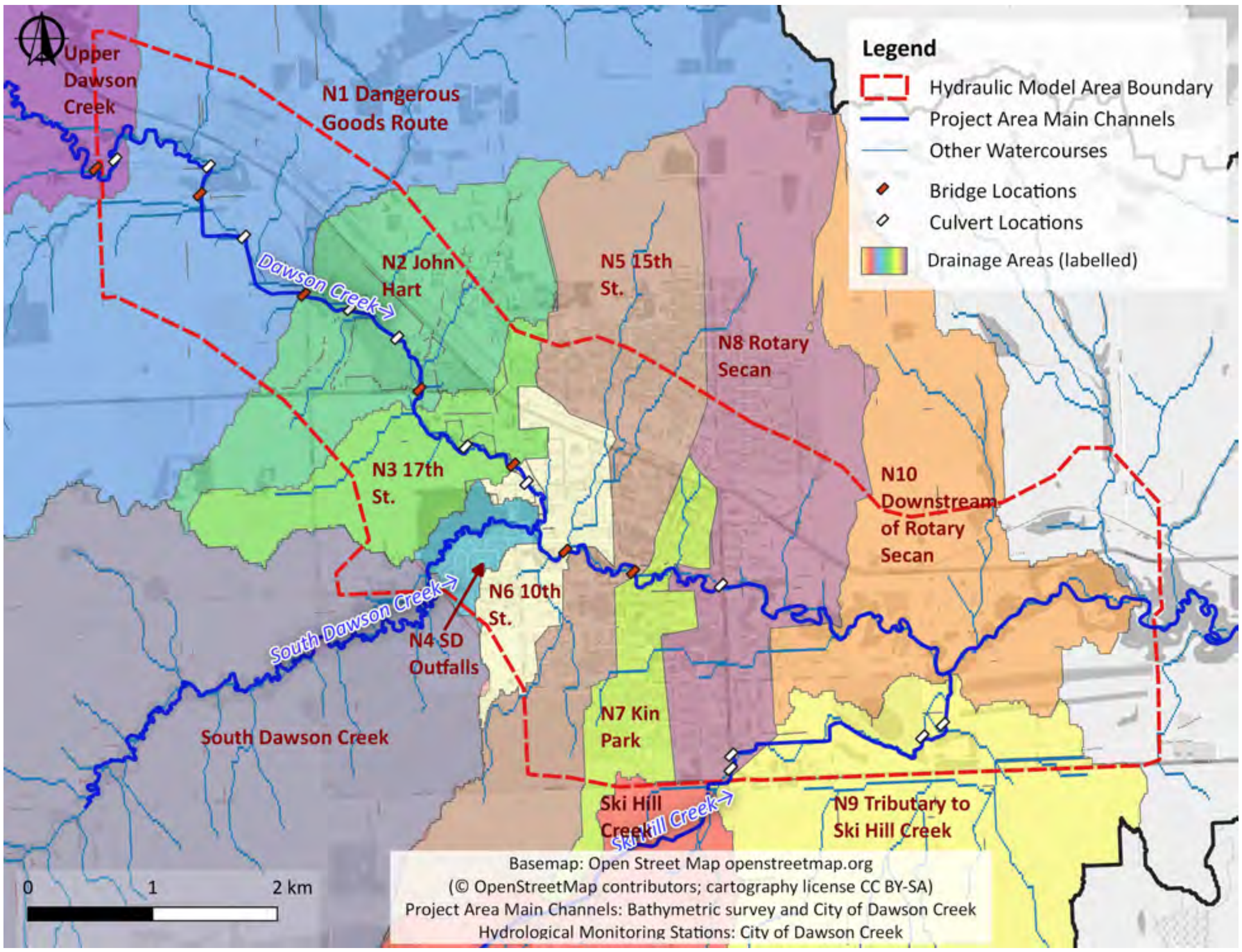

Figure 18: Hydraulic model area boundary and other features used for modelling.

6.2.2 Topographic Surface Processing

The topography of the land and channels is important input for the 2D hydraulic model. Significant effort was made both in the development of the original DEM (see Section 4) and the refinement of the surface for hydraulic modelling (see below).

In order to prepare the DEM for use in the hydraulic model the following processing steps were conducted:

- Bridge decks were replaced with creek bed elevations based on the bathymetric survey.
- Culverts were replaced with creek bed elevations based on the upstream and downstream elevations.

- Where "no data" values occurred in the spatial dataset, elevations were assigned or patched from adjacent points.

Bridges and culverts were added back to the model later, as discussed in Section 6.2.5. The horizontal resolution of the DEM used for this study is 0.5 m and elevations are referenced in Metric and NAD 83 (CSRS) UTM Zone10N (CGVD2013). The resulting DEM is presented in Figure 19. The figure also shows the model mesh (described in the next section).

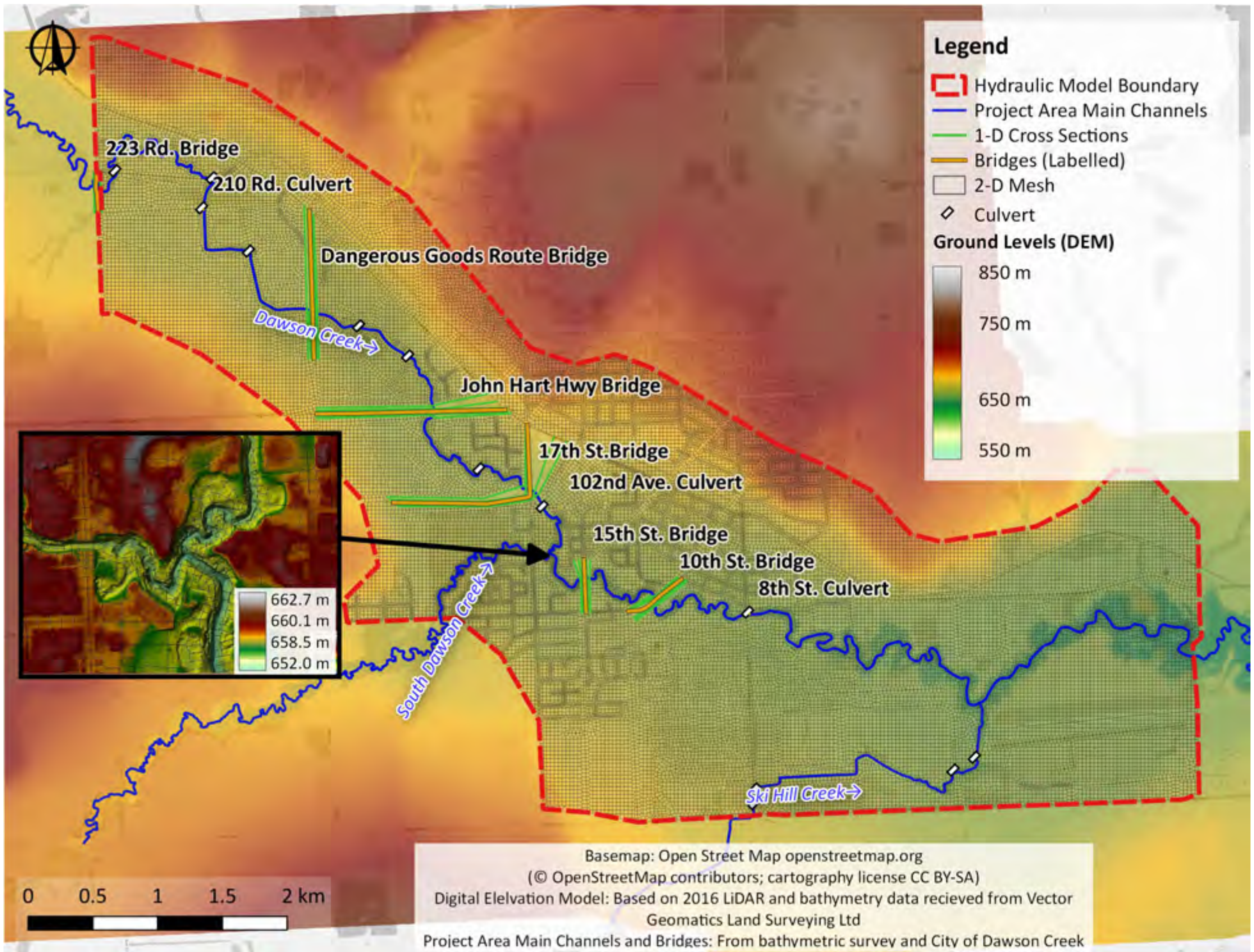

Figure 19: Hydraulic model boundary with DEM and model mesh, and major crossings.

6.2.3 Model Geometry

The model geometry relies on the elevation information from the DEM to enable hydraulic calculations. The Dawson Creek model includes two main types of geometry – a 2D model mesh for most of the system and 1D components for some crossings. Details about this approach are presented below.

6.2.3.1 <u>2D Model Mesh</u>

A model mesh was developed to represent the underlying topographic and bathymetric information. The mesh is a grid (of cells with 3 to 8 sides) that subdivide the project area into smaller elements (Figure 20).

For each element, the modelling software computes two-dimensional results for depth and velocity; horizontal velocity and depth vectors are calculated.

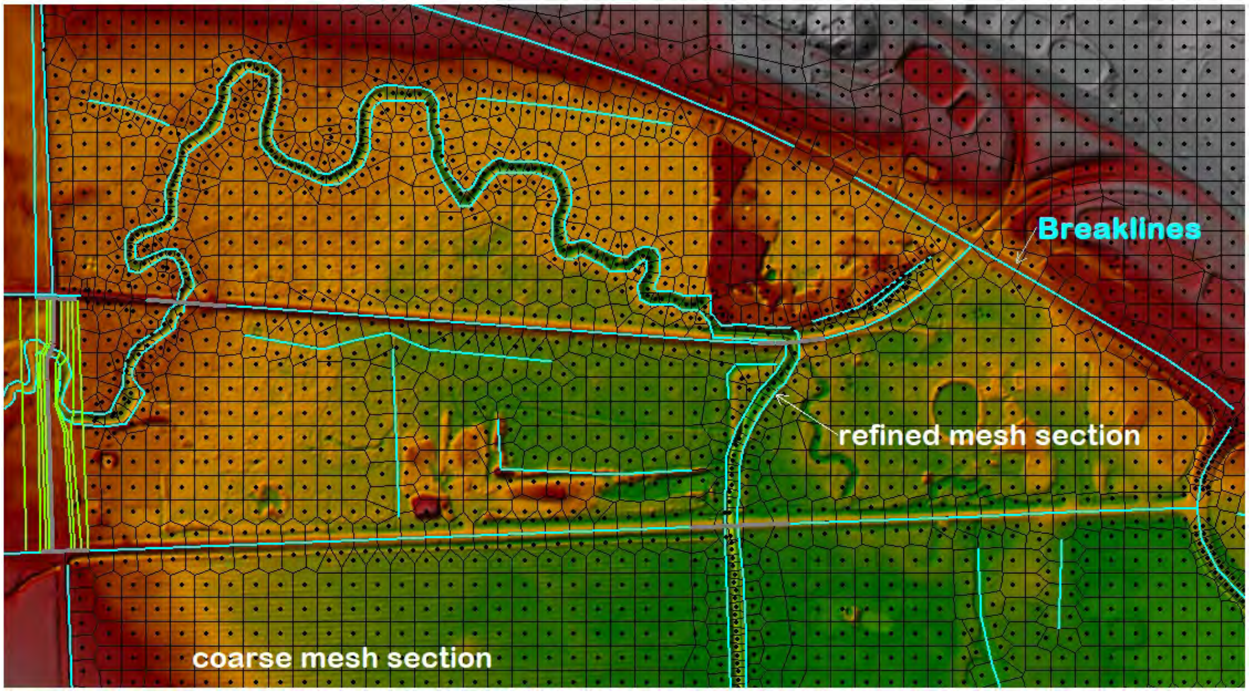

Figure 20: Model mesh with refinement breaklines, as well as coarse and fine mesh examples.

The mesh cell size is a key model parameter. A finer grid incorporates subtle changes in the bathymetry, while a coarser grid is more efficient in terms of computational time. Cell size is an important factor in the stability of the model; the cell size should be small enough to capture detail without abrupt changes and without greatly impacting computational times. The model produces a single water surface elevation for each cell, so it is important to reduce large elevation differences for the model to run efficiently and effectively. The final cell size was selected to balance model accuracy, stability, and run time. The 2D model mesh is composed of cells from 6 m by 6 m in high-resolution areas with key infrastructure to 30 m by 30 m in coarse areas (see Figure 20). To align the edge of ridges (streets) and trenches (river reaches), breaklines were enforced in the mesh (Figure 20). The breaklines align the flow parallel to features with a user-defined cell size.

6.2.3.2 1D Model Features

HEC-RAS does not currently have a straightforward way to model bridges within the 2D domain. Two approaches were considered to model the bridges. The first approach is the traditional method with 1D cross-sections connected to the 2D domain. The second approach is to model the bridges as 2D area connections that implement culverts (rather than bridge) calculations. We applied the first approach with all bridges, except for the 8th St. Bridge, which was modelled using 2D area connections. We considered the built-in 1D bridge equations to be more reliable in the absence of robust data available for calibration. The culverts, including the 102nd Ave. crossing, were modelled in the 2D area.

To properly model the bridges, the mesh was divided into 6 sections. Each section is connected to the next using 1D elements, which include cross-sections and 2D flow area hydraulic connections. The cross-sections representing the main bridges are shown in Figure 19. This configuration was selected based on an iterative process as well as modelling and data limitations (see section 6.2.5).

6.2.4 Manning's Roughness Coefficient

Manning's roughness coefficient or Manning's n represents the resistance to flows in channels and flood hazard areas. Typically, the user assigns an initial Manning's n based on land use and river characteristics and adjusts the values during calibration. For this model, the Manning's n was derived by using a varying land cover dataset. A Manning's n value was assigned for the land cover types, as shown in Figure 21. Additionally, Manning's n values were refined at each bridge based on field photographs and bridge characteristics.

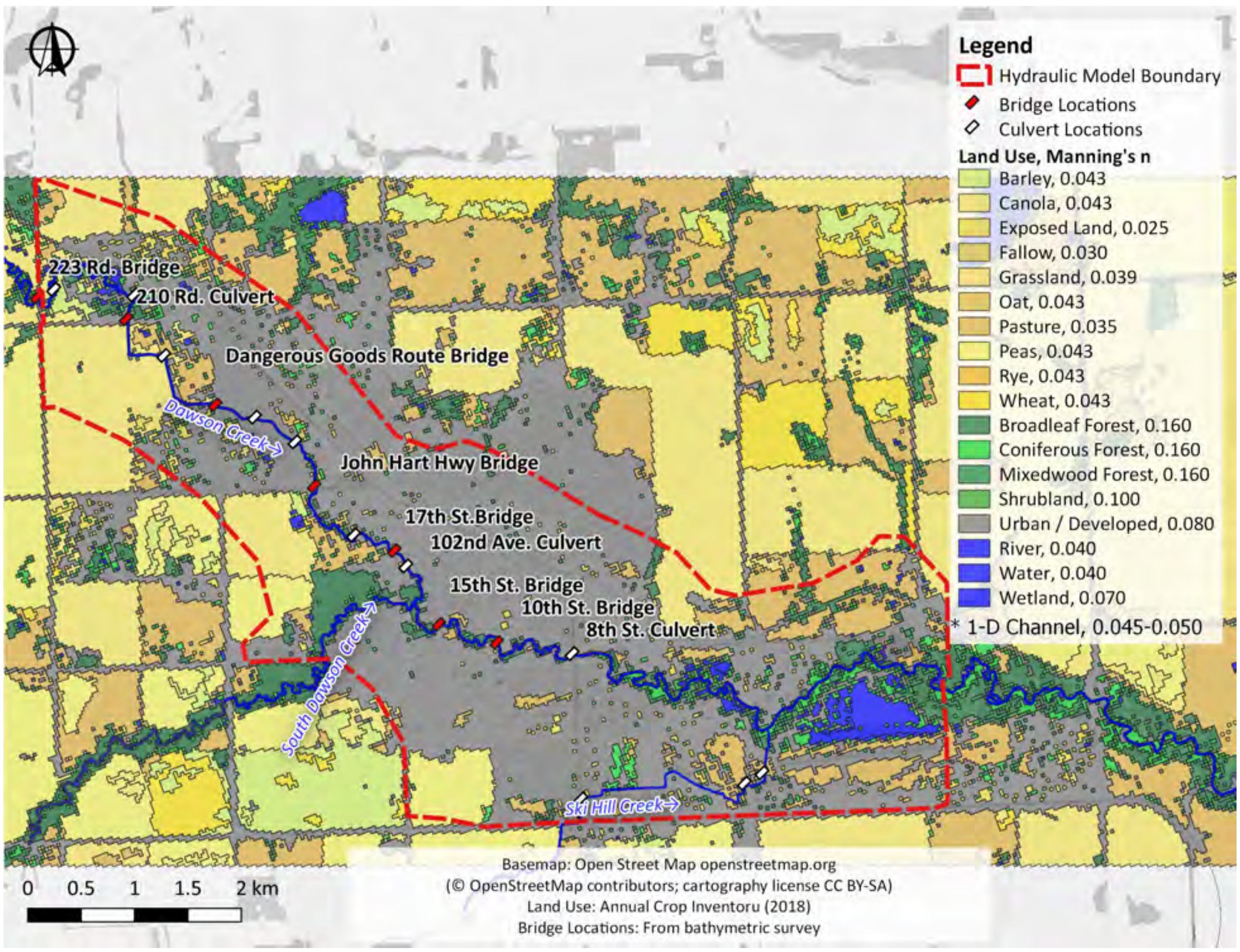

Figure 21: Land use and Manning's n values.

6.2.5 Representation of Hydraulic Structures

The model included 6 bridges and 13 culverts on the project area main channels (Table 13, Figure 22). The geometries of the structures represented in the model were based on information from the field survey (see Section 4), design and as-built drawings, and satellite imagery. Table 13 also indicates the major crossings that were analyzed for the hydraulic analysis of the mitigation options evaluation (Section 9.1).

Table 13: Details for crossings simulated in the hydraulic model, including priority features for results analysis in the mitigation options evaluation.

ID	Name	Creek	Representation in Model	1D or 2D Domain	Mitigation Options Evaluation
1	223 Rd.	Dawson Creek	Bridge	1D	✓
2	Rail	Dawson Creek	Culvert	2D	
3	Reasbeck Rd.	Dawson Creek	Culvert	2D	
4	210 Rd.	Dawson Creek	Culvert	2D	
5	Ditch	Dawson Creek	Culvert	2D	
6	Dangerous Goods Rt.	Dawson Creek	Bridge	1D	✓
7	Golf Course	Dawson Creek	Culvert	2D	
8	Golf Course	Dawson Creek	Culvert	2D	
9	John Hart Hwy	Dawson Creek	Bridge	1D	✓
10	Park Bridge	Dawson Creek	Culvert	2D	
11	17th St.	Dawson Creek	Bridge	1D	✓
12	102nd Ave.	Dawson Creek	Culvert	2D	✓
13	15th St.	Dawson Creek	Bridge	1D	✓
14	10th St.	Dawson Creek	Bridge	1D	✓
15	8th St.	Dawson Creek	Culvert	2D	
16	Highway 2	Ski Hill Creek	Culvert	2D	
17	122nd Ave.	Ski Hill Creek	Culvert	2D	
18	Airport	Ski Hill Creek	Culvert	2D	

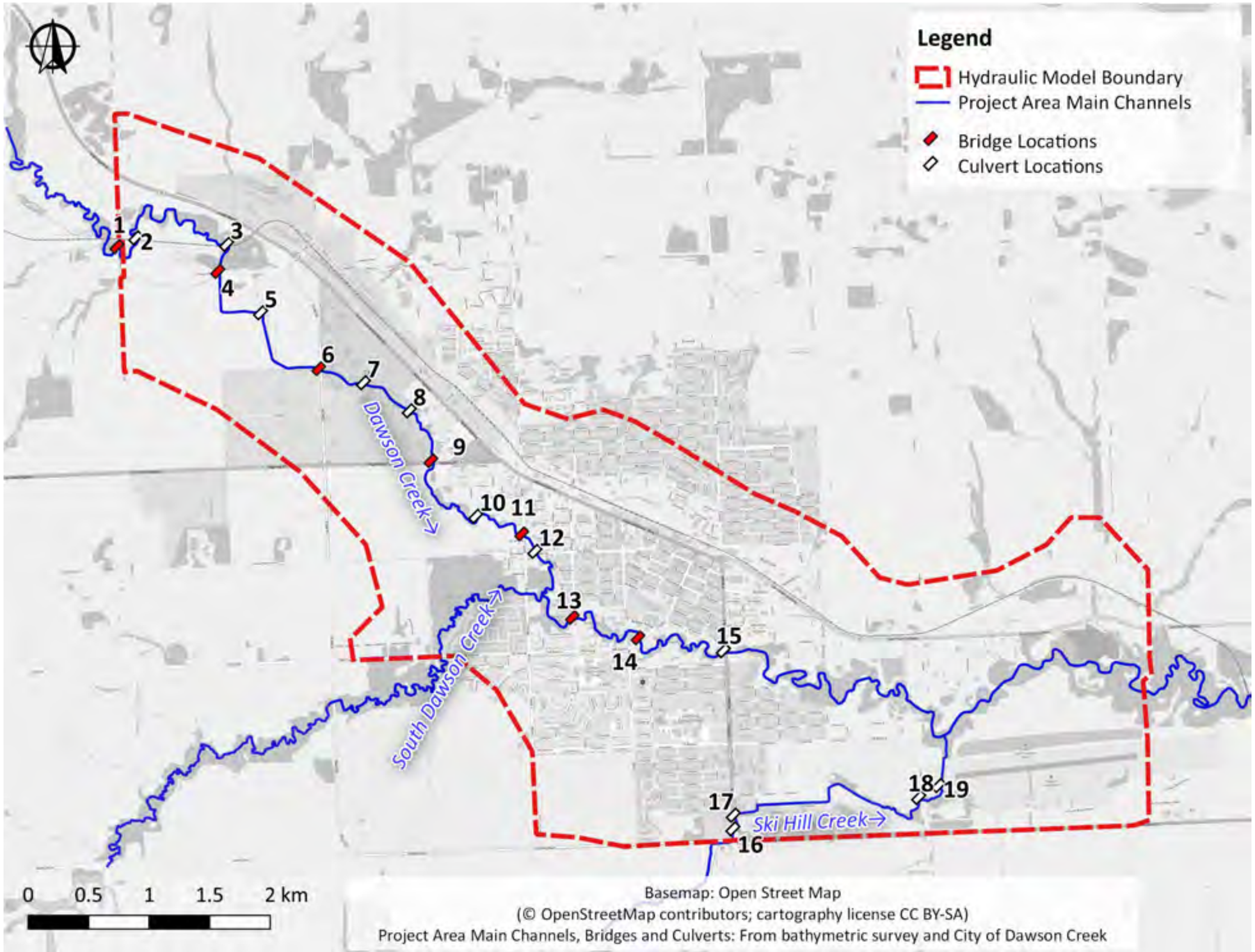

Figure 22: Crossing locations labelled by their identifier (ID).

Recent structural projects that are relevant to this flood mapping project are as follows:

- The City upgraded the 15th St. crossing (ID: 13) from culverts to a bridge, and rebuilt the bridge at 10th St. (ID: 14); both were completed in 2017.
- The Ministry of Infrastructure and Transportation (MoTI) have two ongoing reconstruction projects. The 8th St. crossing (ID: 15) will see the culverts replaced by a bridge, with project completion scheduled in 2021. At Rolla Rd. (downstream from hydraulic model boundary), the bridge is being realigned and reconstructed and is scheduled for completion in 2020.
- The City upsized culverts at the Dawson Creek airport (ID: 18) in 2019.

For the 2016 flood model runs, the old structures at 15th St., 10th St., and 8th St. were included in the model. The new structures at these locations were included under existing conditions model runs.

6.2.6 Boundary Conditions

A hydraulic model is forced by controlling flow through boundaries at both the upstream and downstream ends of the system. For the Dawson Creek model, four external boundary lines were used, corresponding to each of the project area's main channels. In addition, the model included ten other inflow points to represent discharge points from the City stormwater system, and a prescribed water surface elevation downstream. The prescribed flows used at each of the boundary and inflow points addressed the various existing condition and climate change scenarios, as presented in Section 6.4.

The boundary conditions establish the water surface elevation, flow conditions, or normal slope for the model inflow and outflows. The boundary condition is created in the geospatial interface and time series data are entered in the flow data editor. Unsteady flows, which change over time, are often used to capture the change in flow, stage, and velocity over the duration of an event. Steady flows, or a constant value for the simulation, are often used for known maximum flows or for additional inflow points. Both steady and unsteady flows can be used for different conditions across the model domain, as implemented in the Dawson Creek hydraulic model. Large inflows like that of the main creek and South Dawson Creek are input as unsteady flows while smaller tributary or piped stormwater inflows are input as steady flows. Maintaining the steady flow condition at peak flows for several areas is a more conservative approach for accounting for the flow through the system.

6.2.7 Initial Conditions

Initial conditions were set to a 4-hour warm-up time and were applied to the model to provide stability. The model warm-up time is applied in a steady state to the initial input flows. After this warm-up, the channel conditions for the first time step accurately represent the flow of water in a wetted channel. Stability, especially between the 1D and 2D connections, is crucial for a smooth simulation and reasonable results.

6.2.8 Run Parameters

A summary of the model with simulated flow conditions, time steps, and total run time is in Table 14. The time steps are determined by balancing the overall computational time (longer time steps run faster) with model accuracy and stability (shorter time steps are sometimes needed). The corresponding time step for each run tends to decrease as flows increase. This is because the solution scheme solves the flow equations based on distance and time. If the flow properties change too rapidly, the calculations destabilize. Thus the 50% AEP event time steps are 12–20 seconds, while the 0.5% AEP time steps are 4–6 seconds. The program goes through these calculations for the entirety of the simulation or run time, which is 4 days for most simulations.

Table 14: Summary of run parameters.

Model Run	Flow Conditions	Time Step (seconds)						Run Time (days)
		50%	20%	10%	2%	1%	0.5%	
Existing Conditions	50%–0.5% AEP	15	10	12	12	12	4	4
Climate Change, 2050	50%–0.5% AEP	15	15	6	12	5	5	4
2016 Flood verification	Estimated 2016 flow	6						4

6.3 Verification

Ideally, a model is developed, calibrated, and validated using observed information. For calibration, model parameters are adjusted to fit model results to observations. For validation, the calibrated model is then tested against a second set of observations. This process provides confidence in the model robustness and results. However, this process requires that observations are available to calibrate and validate the model. For a flood model, high water levels are of concern, therefore observations of water levels in the channel and flood hazard area are needed for peak flow events. Unfortunately, this information was not available and therefore an alternative approach was taken whereby the model was verified to available information. Additionally, a sensitivity analysis was completed to understand the limitations and uncertainties in the results.

The verification process was therefore limited to a comparative analysis based on the observed 2016 flood extent, as estimated by the City of Dawson Creek. The following section describes the processes followed to check the model's performance and refine its parameters.

6.3.1 2016 Flood Extents Data

In 2016, a major flood event occurred in Dawson Creek in the early morning of 16 June 2016. In the late morning, approximately 6 hours after the peak, City staff collected aerial photographs of the conditions. City staff also collected coordinates from ground surveys from observations of "trash lines," which estimate flood high water levels. The aerial photographs and coordinates were used to delineate the estimated extent of the flood in GIS by City staff[16]. The resulting 2016 flood extent layer formed the basis for a comparative analysis with hydraulic model outputs.

Note that while the City's 2016 flood extent layer is the best available flood event data, it is limited in accuracy. For example, the 6-hour lag between the flood peak and the aerial photography means that water levels, and therefore the flood extent, may not be representative of the flood peak. The lack or misrepresentation of trash lines following the flood would result in inaccuracies in the delineation of the extent. Most importantly, the layer does not include information critical to verification such as flow rates and depths.

Figure 23 shows a photograph of the 2016 flood near 102nd Ave. used by City staff to estimate the extent of the 2016 flood.

[16] Pierre Pelletier, GIS Technologist, City of Dawson Creek, personal communication. 27 March 2020.

Figure 23: Aerial photograph of 102nd Ave. crossing area on the morning of 16 June 2016. Source: City of Dawson Creek (text and flow direction arrows by Ebbwater).

6.3.2 Model Comparison Run

To compare the model to observed events, the model was set-up to represent 2016 conditions. Based on the hydrologic analysis, that flood event had an approximate 1.3% AEP (see Section 5.4.3). To reproduce the 2016 flood flows in the hydraulic model, adjustments were made to the hydraulic model for this verification run. The geometry for structures was modified according to the following:

- The recently upgraded crossings at 15th St., 10th St., and 8th St. were modified in the model to reflect the structures that were present in 2016.
- The cross-sectional area of the major crossings in Dawson Creek were reduced or obstructed to simulate debris. This modification was based on aerial imagery and the Urban Systems (2017) report that suggested approximately one third of the structures were obstructed.

Model parameters were incrementally adjusted to fit the hydraulic model results to the City's 2016 flood extent layer. The adjustments included the Manning's roughness coefficient and the obstructed flow area at the structures.

Figure 24 compares the City's 2016 flood extent layer and the hydraulic model results for the 2016 simulation. Generally, the simulation compares well with the City's flood extent layer. To review closely, comparisons between the layers follow Figure 24, from upstream to downstream on the Dawson Creek.

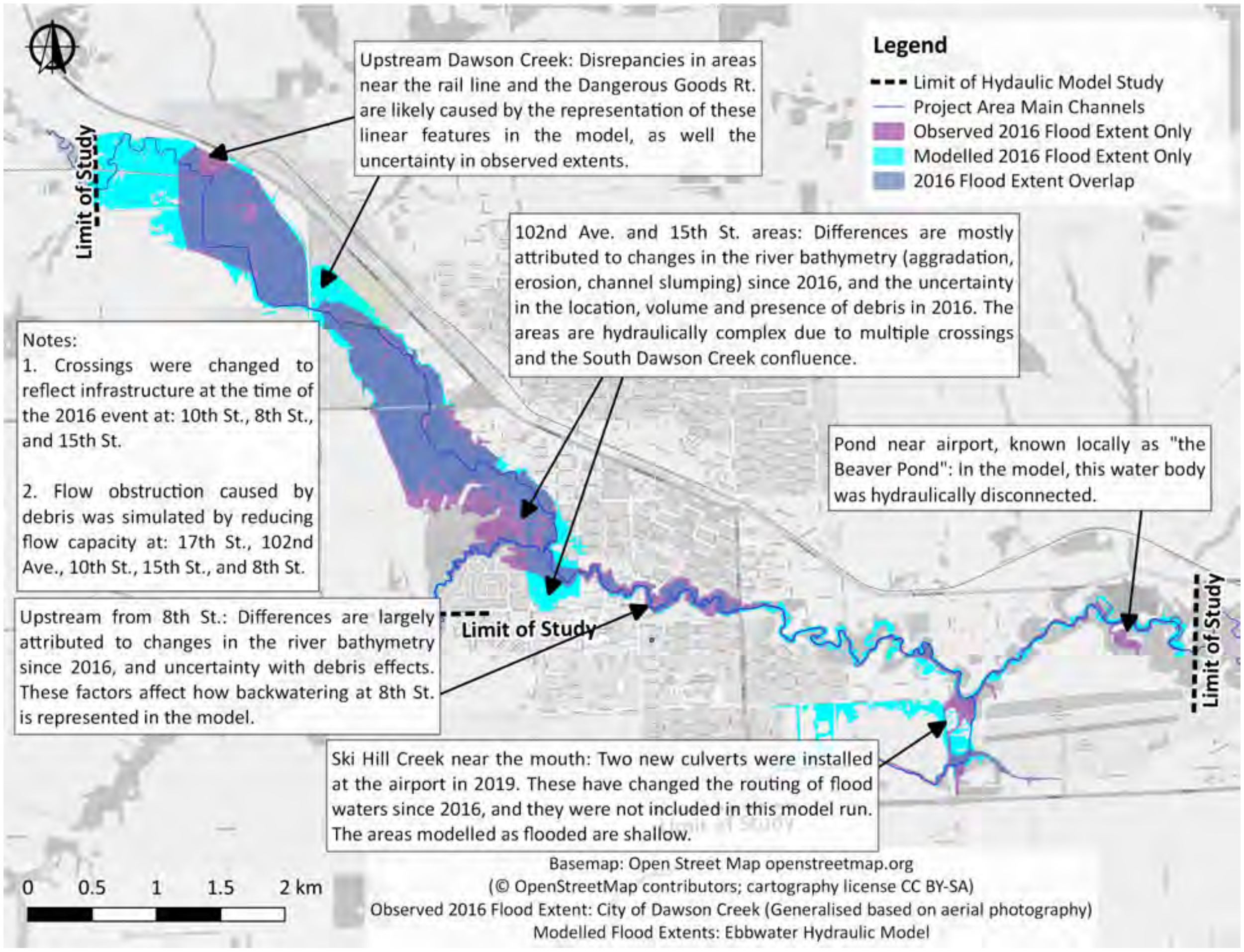

Figure 24: Comparison of the City's 2016 flood extent layer (purple) and hydraulic model flood extents (turqoise).

In the upstream area, the model extents are similar except for a couple of areas adjacent to the Alaska Highway and the Dangerous Goods Rt. This is likely due to uncertainty in the observed extents.

Moving downstream on the main channel, discrepancies are visible in the reach from the 17th St. Bridge and downstream to the 15th St. Bridge (i.e., upstream and downstream from of 102nd Ave). This area is particularly hydraulically complex for the following reasons:

- The two structures within the area are separated by a channel reach of only approximately 200 m. As explained in section 6.2.5, crossings within the hydraulic model were represented in 1D, and were coupled within the 2D model. This approach was considered necessary given the characteristics of the project area's channels. However, the approach presents limitations in areas where structures are close together.
- During the 2016 flood, backflow reportedly occurred due to blockages as far downstream as the 8th St. crossing. With backup occurring over approximately 2 km of the main channel, inaccuracies in the hydraulic model (i.e., those stemming from representation of the topographic surface, roughness coefficient, and other model parameters) would be amplified at the 102nd Ave. crossing.

- The area is located upstream of the confluence with the South Dawson Creek, which affects the hydraulics of the Dawson Creek. Furthermore, these complexities would be exacerbated under the backup conditions.
- There are several beaver dams along the Dawson Creek and on South Dawson Creek (See Appendix F). While this was partially accounted for by obstructing the cross-sectional areas of major crossings in the hydraulic model, the local influences of debris present in other areas was not accounted for. This may have been significant at the confluence with South Dawson Creek. These conditions would have exacerbated the issues related to backup explained in the previous two points.
- Despite the complexities at the 102nd Ave. area, the hydraulic model accurately simulates flood waters flowing down 17th St. prior to overtopping 102nd Ave., which matches anecdotal evidence received from residents.

For the South Dawson Creek channel, the hydraulic model appears to simulate the flood extents relatively well. Between the confluence of South Dawson Creek and the 8th St. crossing, simulated flood extents tended to be slightly larger than the extent provided by the City. This discrepancy could be due to model inaccuracy or inaccuracy in the City's flood extent layer (see Section 6.3.1). Again, discrepancies could be due to backup conditions caused by blockages at crossings in this stretch of the channel.

The stretch of the channel that is downstream of the 8th St. crossing compares well to the downstream model boundary. On Ski Hill Creek, there are discrepancies, particularly near the outlet.

6.3.3 Comparison Summary

Based on the data reviewed for comparison, we consider the hydraulic model to sufficiently simulate flood flows for the project area. For the existing and climate change condition model runs, the geometries of the upgraded crossings at 15th St., 10th St. and 8th St. were incorporated into the hydraulic model. In particular, the 8th St. crossing was designed to increase flow capacity downstream. Therefore, the backup conditions that may have caused inaccuracies in the model comparison are likely to be reduced or eliminated, abating concern about model capabilities. **The model is sufficient and robust for the purposes of flood mapping.**

6.3.4 Sensitivity Runs

Given that calibration was not possible, the model was subjected to a sensitivity analysis. In a sensitivity analysis, model parameters are varied to test the relative impact on overall results. In this case, model sensitivity was tested for roughness and inflows. The model mesh development and sizing, along with model run parameters (e.g. timestep) is not presented explicitly, as significant improvements were made during the model development phase.

6.3.4.1 Roughness

To test the friction coefficient, a manual sensitivity analysis was completed. The Manning's roughness coefficient was varied for ±20% and the model was run for a range of scenarios, namely the 2%, 10%, 20%, and 50% AEP events. The water surface elevations near the bridges remained within ±10 cm for all runs. Furthermore, minor differences were observed in the flood hazard extent, as seen in Figure 25. The comparison of flood extents for the range of Manning's n values show that the model is relatively insensitive to roughness coefficient variations.

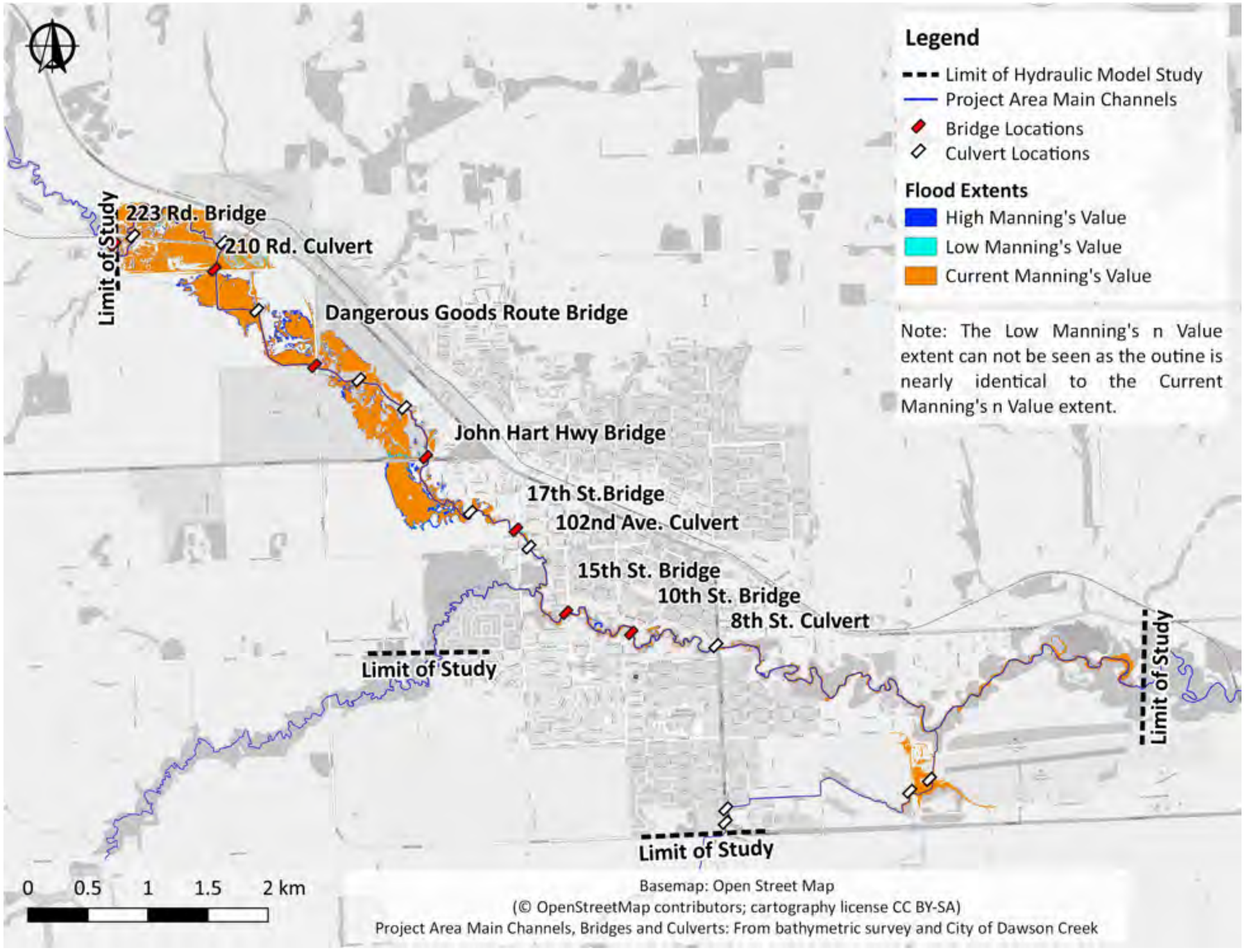

Figure 25: Comparison of flood extents for different Manning's n values for the 20% AEP flood.

6.3.4.2 Flows

Flow sensitivity was determined by re-purposing the model production runs, which include a total of 12 runs with varying flows. As anticipated, the flood extents, especially in the upper reaches are sensitive to flows. This highlights the need to conduct a detailed hydrologic analysis (as presented in Section 5).

6.4 Model Production Runs

Upon completion of the verification, model runs were conducted based on the inflows determined at the boundaries through the hydrologic analysis (Section 5). The model was run for the multiple AEPs under existing conditions and climate change scenarios, as shown in Table 15.

Table 15: Model scenario details.

Time Period	Scenario No.	AEP	Upstream Boundary Peak Flow (m^3/s)		
			Dawson Creek	South Dawson Creek	Ski Hill Creek
Existing Conditions	1	50%	6	5	0.7
	2	20%	11	10	1.5
	3	10%	17	16	2.2
	4	2%	36	34	4.9
	5	1%	49	46	6.6
	6	0.5%	67	62	8.9
Climate Change (2050s)	7	50%	6	6	0.8
	8	20%	13	12	1.7
	9	10%	19	18	2.6
	10	2%	43	40	5.7
	11	1%	60	56	8.0
	12	0.5%	83	77	11.1

Note that the production runs above only include climate runs for the 2050s, and not for longer-term scenarios. This is because, as shown in Section 5.5, the 2050s represent the highest projected flows under climate change; longer-term projections show a decrease in peak flows.

6.5 Results

The following sections summarize results for all model runs. These are presented in multiple formats to help with the interpretation of the information. To facilitate the reader, Table 16 shows how the AEPs used for model runs link with other measures of frequency (i.e., indicative return period and likelihood). The likelihood is based on relative classification. Similarly, Table 16 contains relative classes to describe the magnitude of flood events. In the sections below, the relative flood magnitudes (right-most column, bolded) are used to differentiate between flood events.

Table 16: Linkages between flood frequency and magnitude of the events modelled.

Based on Calculations		Based on Relative Classes	
AEP	Return Period (indicative)	Likelihood	Magnitude
50%	2 year	Very likely	**Very low**
20%	5 year	Likely	**Low**
10%	10 year	Moderately frequent	**Moderately low**
2%	50 year	Moderately infrequent	**Moderately high**
1%	100 year	Rare	**High**
0.5%	200 year	Very rare	**Very high**

6.5.1 Water Levels and Points of Interest

Key points of interest were determined based on stakeholder feedback obtained from the Flood Mitigation Planning Report (Ebbwater, 2018). The points, shown in Figure 26, are well known locations to residents in the community and were impacted by flooding during the 2016 event.

Figure 27 compares the maximum flood depths at these points for the various scenarios listed in Table 15. For the very high magnitude event (0.5% AEP), all points of interest are flooded. The golf course is under approximately 1.5 m of water, businesses and homes on 17th Street are under approximately 0.8 m of water, and the funeral home is under approximately 0.3 m of water. For the high event (1% AEP), all points of interest are still flooded, but they are under less water. For the moderately high event (2% AEP), only 3 points are under water, and for lower magnitude events (10% to 50% AEPs), only the golf course is flooded.

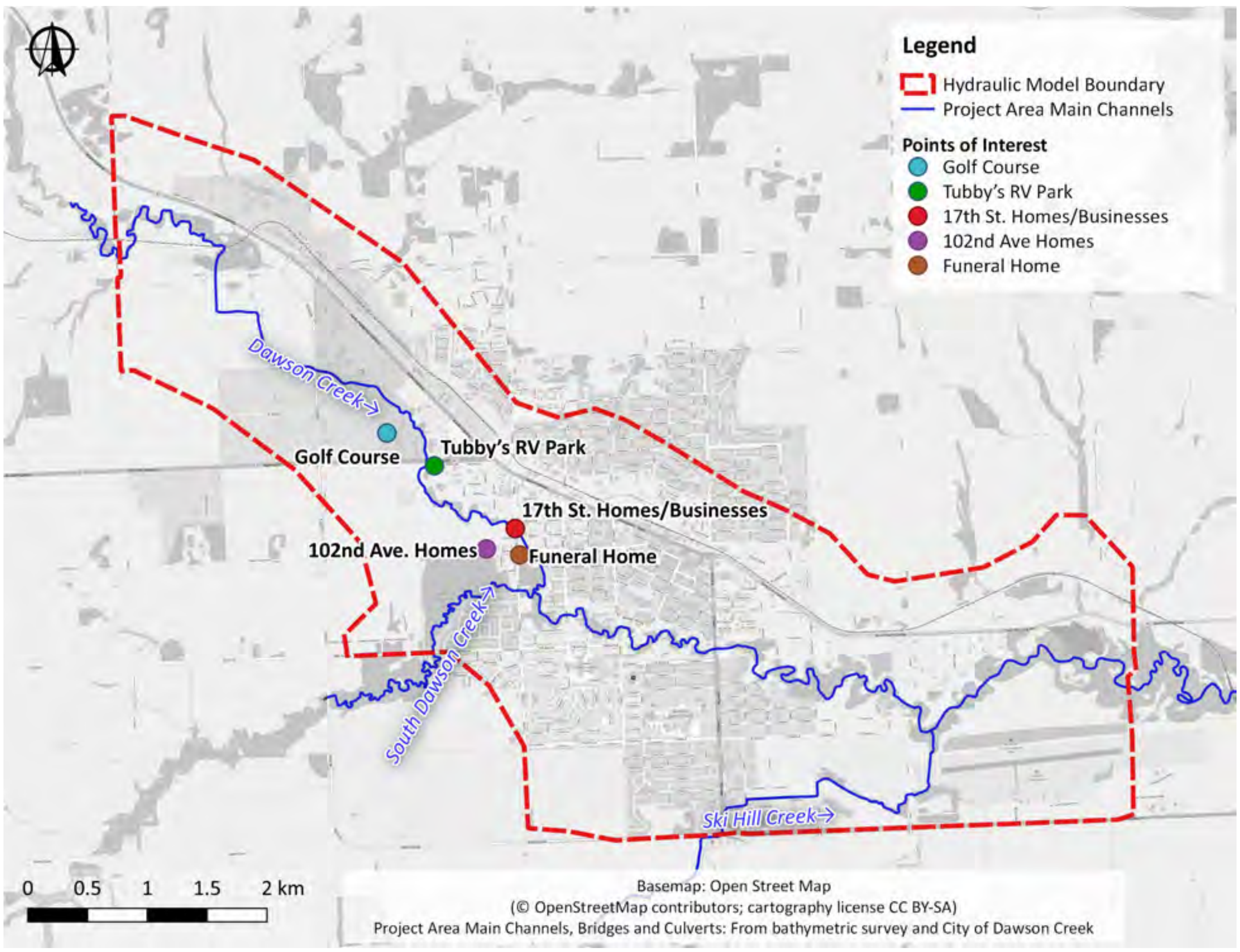

Figure 26: Key points of interest.

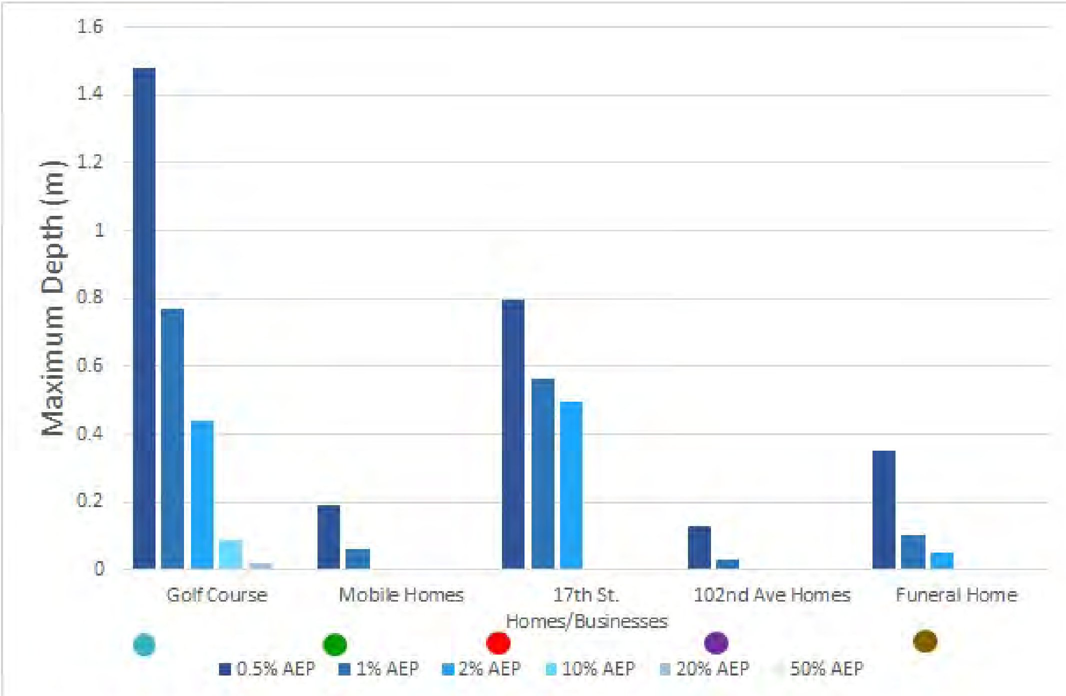

Figure 27: Comparison of water depth for various AEPs at points of interest.

This analysis highlights the importance of considering multiple flow events. For the lowest magnitude event (50% AEP), only the golf course is flooded. However, some areas are flooded for moderately high events (2% AEP), such as the funeral home and the homes/businesses along 17th St. This is consistent with observations during the 2016 event, which was estimated as having a 1.3% AEP. This means that mitigation options should consider multiple events, especially moderately high magnitude events (2% AEP).

The points of interest analysis also shows that flooding is relatively binary in the core of Dawson Creek, where the channel is incised. The flood hazard area remains dry for flood magnitudes lower than the moderately high event (2% AEP), as the flow is contained within the channel. Above this flood magnitude, the flow rapidly spills overland. This is in contrast to the golf course area, where the channel is less incised, and the flood hazard area slopes are more gradual. In the golf course area, the depth and extent of flooding correlates well with the increase in flow volume (see first grouping of bars in Figure 27). This highlights the need to consider different mitigation options that address the incised channel reach area of 102nd Ave., and the upstream channel reach with gradual flood hazard area slopes near the golf course.

6.5.2 Flood Extents

The extent of the flooded area is a key piece of information to support future planning and policy. Figure 28 compares the flood hazard extents for the very high (0.5% AEP), moderately high (2% AEP), and very low (50% AEP) magnitude flood events. Table 17 compares the extents of the flooded areas for the existing condition and climate change scenarios. As shown in the hydrologic analysis (Section 5.5.3), out of the 3 future climate change periods (i.e., 2030s, 2050s, and 2080s), the projected inflows are greatest for the 2050s period. Therefore, Table 17 shows the climate change flood extents for the 2050s only.

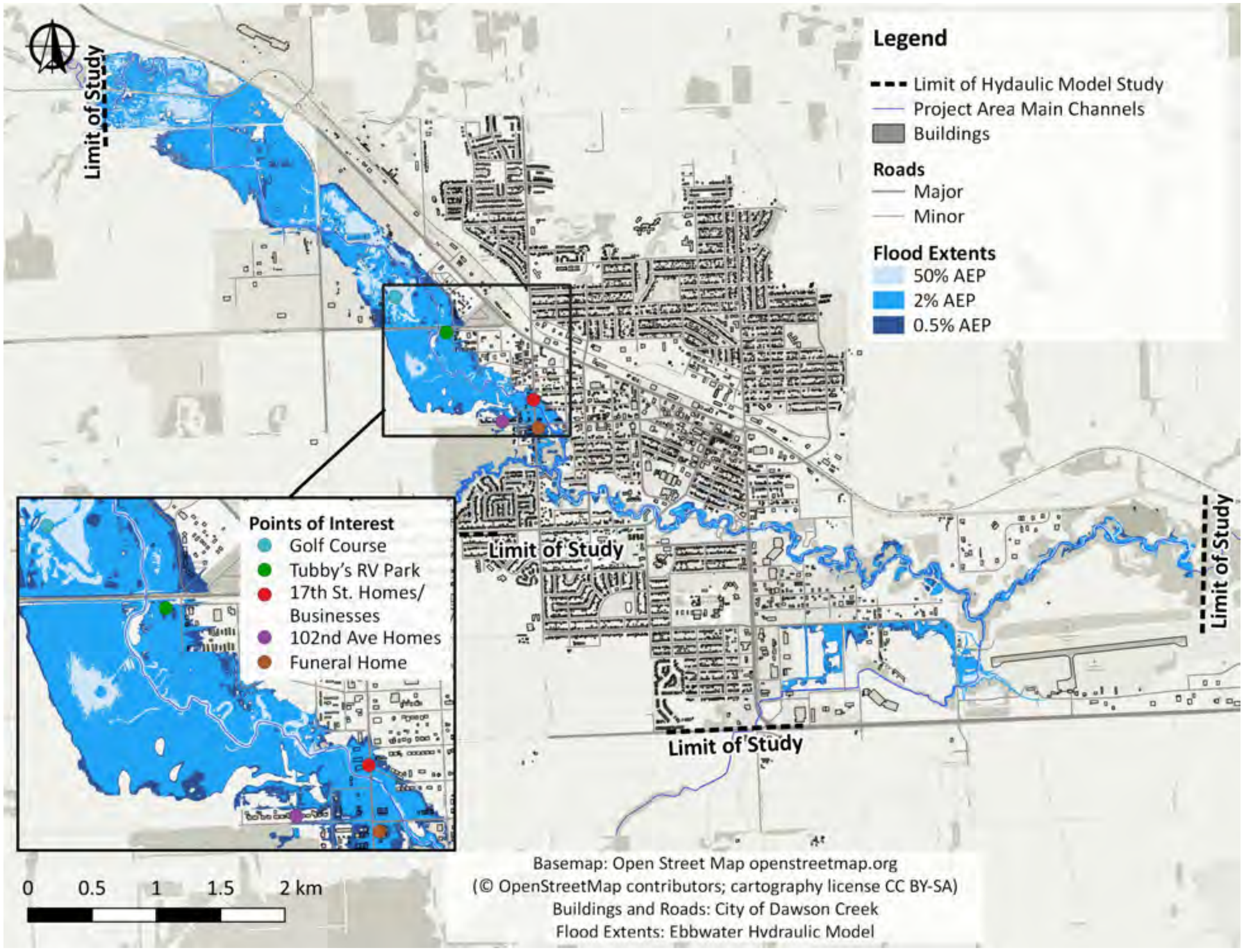

Figure 28: Flood hazard extent comparison for selected AEPs capturing the range modelled.

Overall, Figure 28 shows that extents between different flood events do not change significantly with changing AEP in the confined and steeper lower mid and lower reaches of the system. However, in the upper reaches, where the channel has a shallower slope and larger flood hazard area, the differences are more pronounced.

Under climate change, Table 17 indicates that the flood extent for the low magnitude flood event (20% AEP, 1.5 km^2) comes close to being equivalent to the same flood extent for the moderately low event (10% AEP) under existing conditions (1.6 km^2). What is notable is that the largest relative changes between now and the 2050s is found with the lower magnitude flood events (e.g., 25% increase for the 20% AEP flood). Specifically, flood extents of these smaller events are increasing (and, conversely, the events are occurring more frequently). This has considerable importance for policy and planning.

Table 17: Summary of area flooded for existing conditions and climate change (2050s) scenario runs.

Existing Conditions				Climate Change (2050s)			
Scenario No.	AEP	Area (km²)		Scenario No.	AEP	Area (km²)	% Change from Existing Conditions
1	50%	0.59		7	50%	0.63	7%
2	20%	1.2		8	20%	1.5	25%
3	10%	1.6		9	10%	1.8	13%
4	2%	2.5		10	2%	2.7	8%
5	1%	2.7		11	1%	3.0	11%
6	0.5%	3.1		12	0.5%	3.3	6%

6.6 Limitations

All hydraulic models have strengths and weaknesses, and it is important to understand these so that the model results can be used appropriately. In the case of the Dawson Creek model the following limitations are noted:

1. Bathymetry and topography are the most important inputs to a 2D model. These are generally robust for the Dawson Creek model; however, there are some limitations of note. Specifically, that a 3D model of the main channel was constructed using interpolation of 2D cross-sections. Variation and small errors may be expected between sections. Further, smaller side channels were not surveyed, and LiDAR was used to represent these.
2. The DEM used in the model, along with other geometry inputs (e.g. bridge and culverts) are based on the best available information at the time of the model development. This represents a snapshot in time. It is expected that this will change in future, both because of natural geomorphological process (see Section 8.1 for more details) and with changes to crossing structures.
3. Limitations from the hydrologic analysis (see Section 5.6) are carried through the hydraulic modelling and mapping.
4. Calibration and validation data were not available. A verification process was conducted instead. The model is considered robust, but with additional hydrometric data, could be further tested.
5. The design flows are significantly higher than the verification flows (e.g. for the mainstem the 0.5% AEP peak flow is 98 m^3/s as compared to the 2016 estimated flow of 44 m^3/s). Flow hydraulics will vary with flow volumes (e.g. relative roughness will decrease as cross-sectional areas increase). This is a standard limitation in hydraulic models developed to model large flood flows. In general, this results in precautionary results; modelled water levels for design events may be very slightly higher, than if information was available to adjust roughness levels down for larger events.
6. Model input flows were represented as a drain rather than a hydrograph in order to add to the model stability. This means that the beginning of the simulation started with the peak flows and decreased with time. The hydraulic changes such as the minimum and maximum water surface elevations are captured as the water recedes.
7. To appropriately include the bridge structures, they were included as 1D structures, within a larger 2D domain. This adds an additional potential for error at the 1D-2D model boundaries.

8. The model does not consider localised debris. The Dawson Creek system is known to have beaver dams and other debris in the system during flood events. This will affect local water levels, and it is not possible to represent these in the model.

7 Flood Mapping

In this study, flood maps have been produced to show water depths for selected scenarios. A set of regulatory and hazard severity maps for one scenario were created, as defined by the *Provincial Guidelines*. Due to the size of the study area, the City of Dawson Creek has been divided into 2 map tiles, which ensure that maps can be shown at an appropriate resolution. In this section we explain the 3 types of maps produced; the information contained in each can support flood policy and planning in their own specific ways.

7.1 Flood Depth Maps

Flood depth maps provide a detailed assessment of flooding, showing not only the extent of flooding but also the depth of water on the land. The depth of water is directly related to flood impacts in an urban environment. For instance, 10 cm of flooding can cover streets and cause nuisance effects, such as temporary interruption of traffic. On the other hand, larger water depths can flood homes, with more significant impacts. As an example, the potential impacts of flooding at different depths are described in Table 18 for a residential building. Note that these consequences were originally developed for a small and well-resourced local government, and variations for the City of Dawson Creek would be expected.

Table 18: Description of potential damage and disruption consequences of flooding at different depths for a single- or multi-family residential building (adapted from Ebbwater Consulting & Compass Resource Management, 2018).

	Minor Flooding (0–10 cm)	**Moderate Flooding (20–40 cm)**	**Severe Flooding (80–100 cm)**
Condition	Water laps up at doorstep, may enter the house through crawlspace/basement windows, flood garages.	Water in house on main level, crawlspaces/basements likely flooded.	Extensive flooding in house and extensive flooding in crawlspaces/basements.
Damage	No significant damage to residential structures, though damage to contents may occur in garages and crawlspaces. Damage likely less than 200 $/m².	Moderate damage to structures, higher damage to contents in basements and main level, including furnaces and water heaters, major appliances. Damage likely 200–300 $/m².	Considerable damage to structure, extensive damage to content, most major appliances, electronics, furniture on main level and in basements. Damage likely 580–610 $/m².
Disruption	Residents not likely required to leave their homes, but will need to clean up yards and possibly basements. Disruption likely over a week. Limited emergency response required.	Residents likely displaced from homes for several days and weeks emergency response likely needed for elderly and people with disabilities, etc.	Residents likely displaced for 1–2 weeks and disrupted for a month. Emergency response needed including possibly addressing utilities interruptions outside flooded area.

In this study, 12 flood scenarios were considered to map flood depths. These included the 50%, 20%, 10%, 2%, 1%, and 0.5% AEP events for existing conditions and for climate change. For climate change, results were mapped for the future period centred on 2050. In the hydrologic analysis, this was the period that showed greatest changes relative to existing conditions (see Table 11). The map tiles for the scenarios are provided in the Flood Hazard Map Atlas (Appendix D).

The flood depth maps can be used to understand the maximum likely flood depths and extents for a particular scenario. This is useful for flood planning, including emergency management.

Presented below are sample flood depth maps for the 0.5% AEP flood under existing conditions (Figure 29) and for the 0.5% AEP flood under climate change (Figure 30). As mentioned above, further flood depth maps are provided in the accompanying Riverine Flood Hazard Map Atlas (Appendix D).

Overall, water depth maps showed that, both the depths and extents between different flood events change significantly for events of different magnitude. In contrast, the climate change runs and the existing conditions runs for the same AEP floods have relatively small differences in flood extents, however, differences in depths can be easily observed.

7.2 Regulatory Flood Construction Level Map

As described in Section 2, the Province has developed specific guidelines for flood mapping to support regulations. This includes the development of mapping that shows flood elevations for the 0.5% AEP event plus a freeboard of 0.6 m.

An example of the regulatory FCL map for the City of Dawson Creek is presented in Figure 31. This map has been produced to meet all relevant *Provincial Guidelines.* The regulatory FCL map is provided in the accompanying Flood Hazard Map Atlas (Appendix D).

7.3 Hazard Severity Map

During flood events, areas with combinations of high flood water depth and velocity are associated with a higher number of mortalities. Flood hazard maps are critical to identifying these areas for building policy and planning, and emergency management. According to the UK Environment Agency and the UK Department for Environment, Food and Rural Affairs (HR Wallingford 2006) and as mentioned in the *Provincial Guidelines* the hazard rating can be calculated as:

Flood Hazard Rating (HR) = debris factor + depth x (velocity + 0.5)

Where the debris factor is a factor that can take the values 0, 0.5, or 1, depending on the probability that debris will lead to a significantly greater hazard. In the present study we excluded the debris factor in the absence of data to support a selected number. The hazard severity map layer was generated in QGIS using the model's peak depth and velocity outputs and can be found in Figure 32. A hazard rating classification was developed for the needs of this project and can be found in Table 19.

Table 19: Hazard Rating Classification (based on a UK hazard rating classification framework from (Surendran *et al.*, 2008))

Hazard Rating (HR)	Hazard to People Classification	Description
≤ 0.75	Low	• Very Low Hazard (Caution): Flood zone with shallow flowing water or deep standing water
0.75 to 1.25	Moderate	• Danger for Some (includes children, the elderly, and the infirm): Flood zone with deep or fast flowing water
1.25 to 2.0	Significant	• Danger for Most (includes the general public): Flood zone with deep fast flowing water
> 2.0	Extreme	• Danger for All (includes emergency services): Flood zone with deep fast flowing water

7.4 Example Maps

Table 20 lists the flood hazard maps contained in the Flood Hazard Map Atlas, and shows the map examples provided on the following pages. The examples show the Dawson Creek upstream tile in each case.

Table 20: Flood hazard map series provided in the accompanying Flood Hazard Map Atlas. A freeboard (0.6 m) was added for the Regulatory map, but not for the other map series.

Map Type	Time Period	Scenario	AEP	Freeboard	Example
Depth Map	Existing Conditions	1	50% AEP	No	
		2	20% AEP	No	
		3	10% AEP	No	
		4	2% AEP	No	
		5	1% AEP	No	
		6	0.5% AEP	No	Figure 29
	Climate Change (2050s)	7	50% AEP	No	
		8	20% AEP	No	
		9	10% AEP	No	
		10	2% AEP	No	
		11	1% AEP	No	
		12	0.5% AEP	No	Figure 30
Regulatory FCL	Existing Conditions	6	0.5% AEP	Yes	Figure 31
Hazard Severity	Existing Conditions	6	0.5% AEP	No	Figure 32

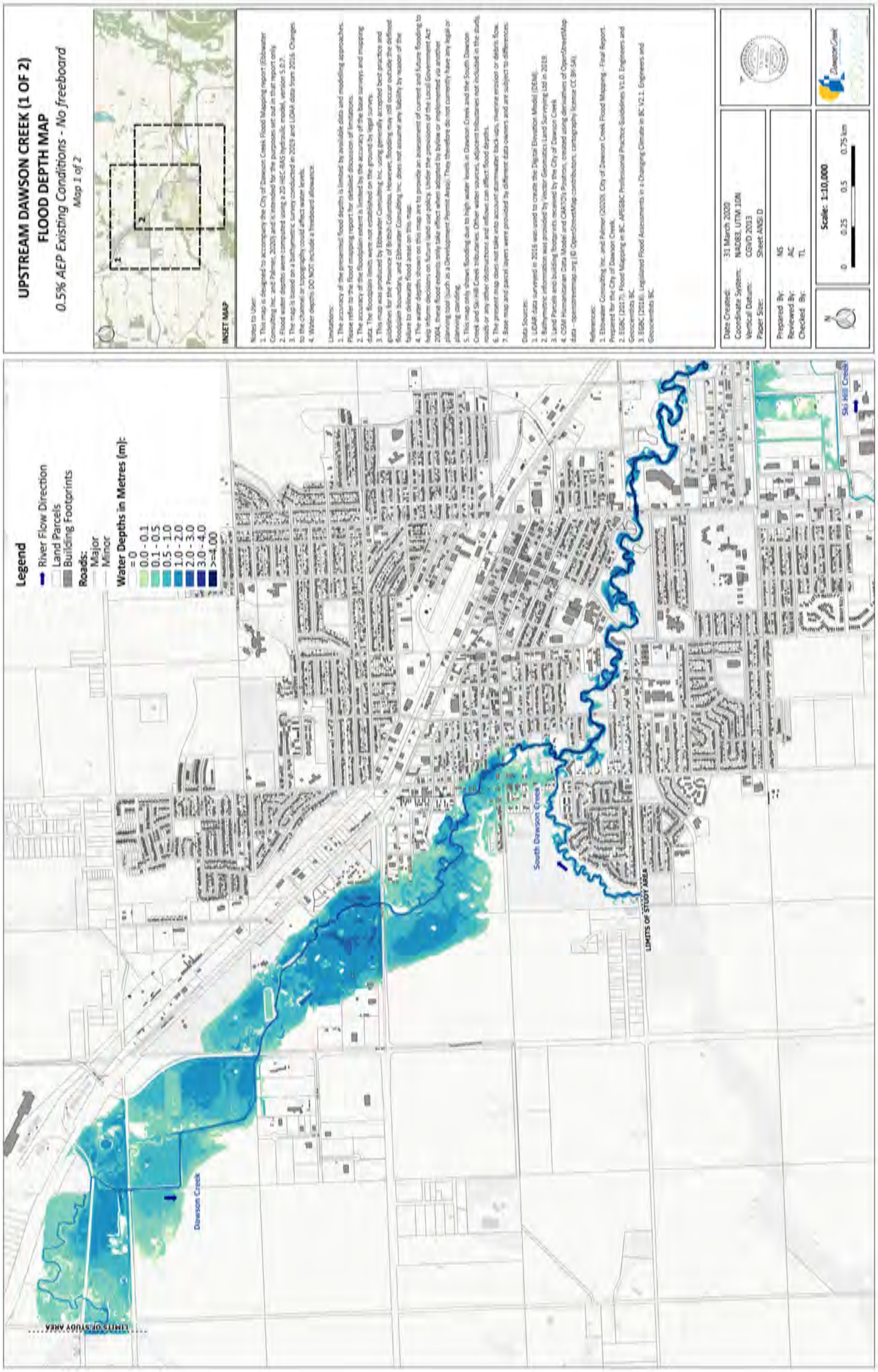

Figure 29: Example flood depth map for 0.5% the AEP flood (existing conditions) for Upstream Dawson Creek map tile.

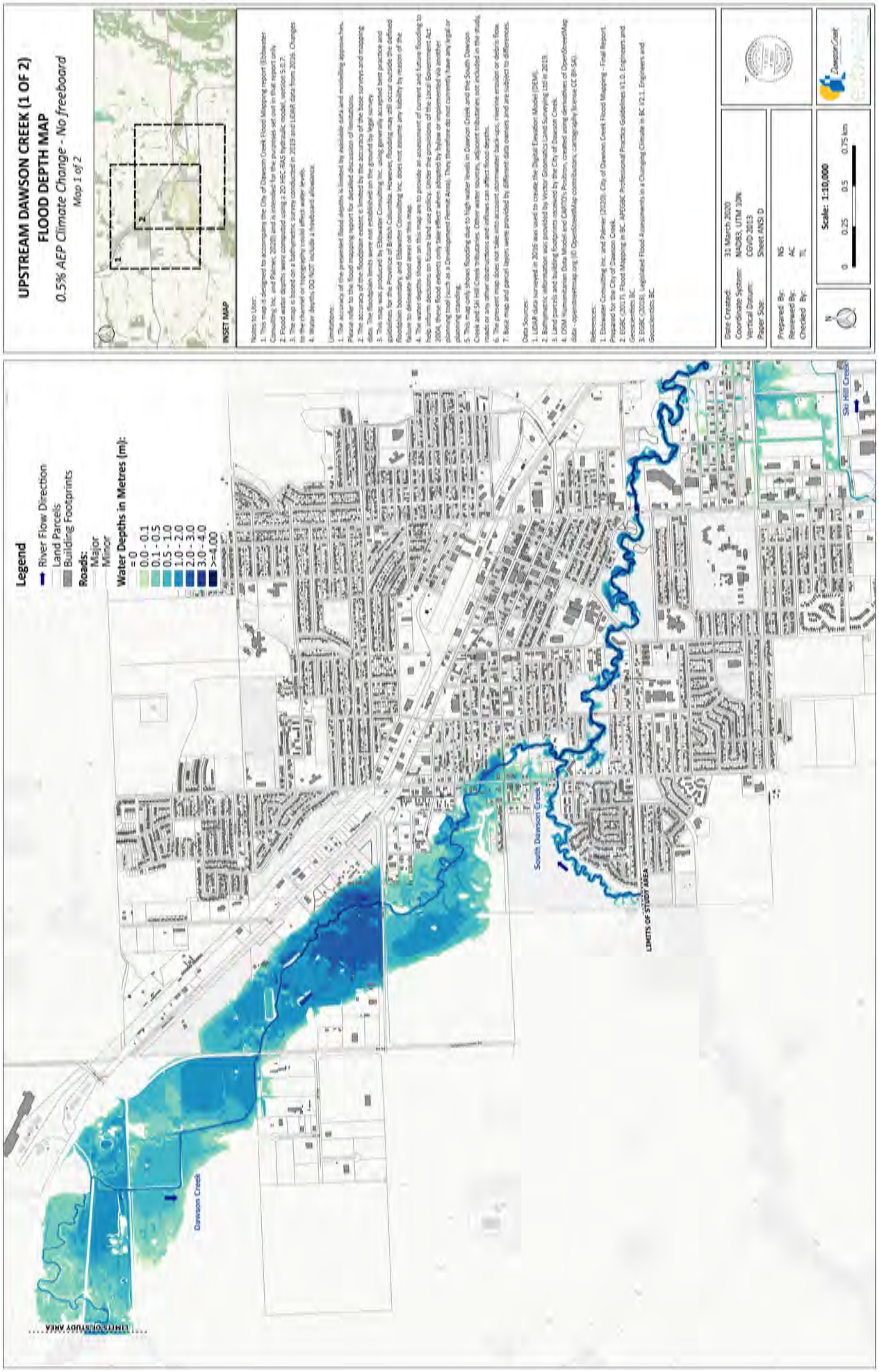

Figure 30: Example flood depth map for the 0.5% AEP flood (climate change) for Upstream Dawson Creek map tile.

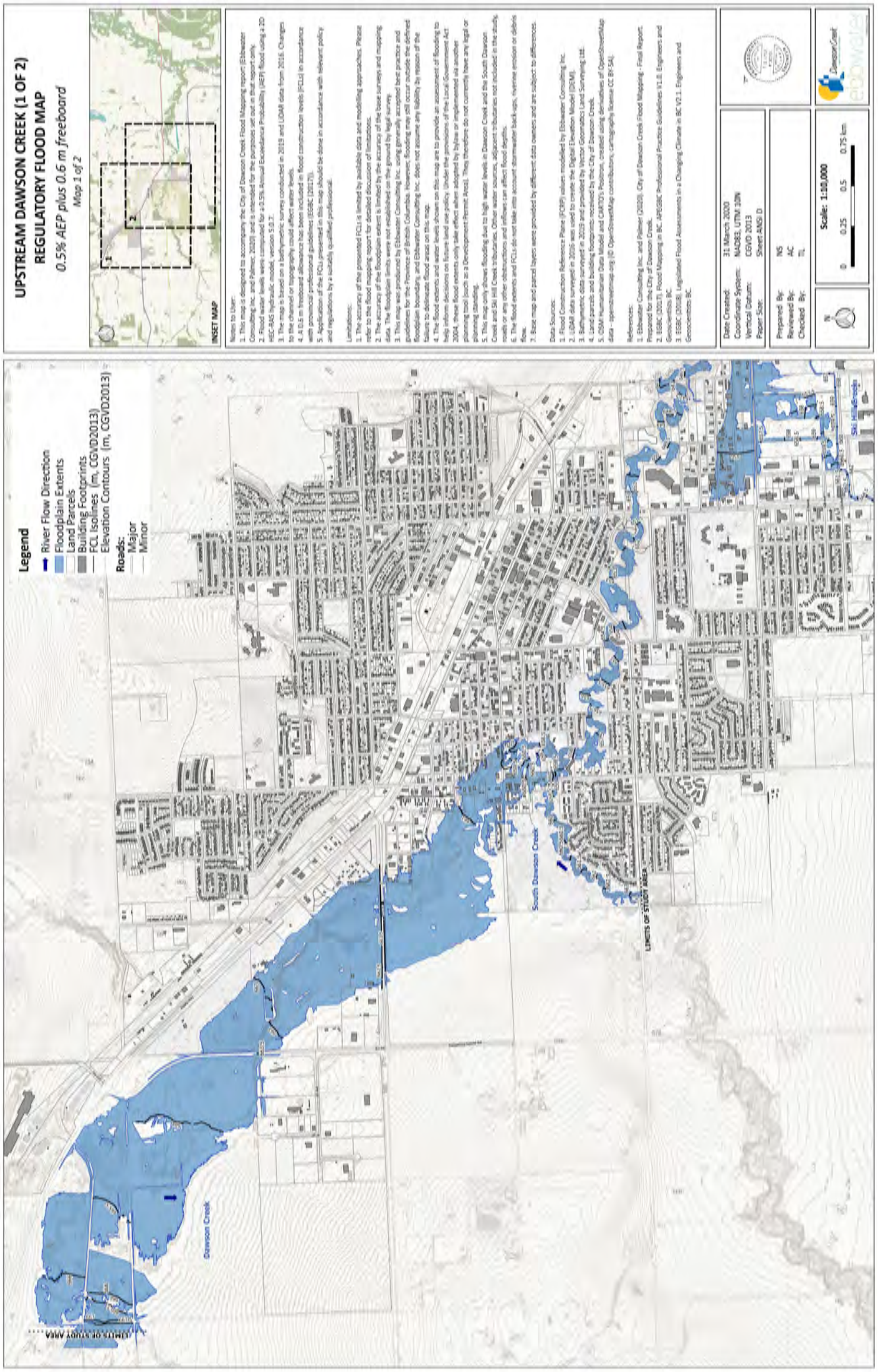

Figure 31: Example regulatory flood Construction level map for the 0.5% AEP flood (existing conditions) for Upstream Dawson Creek map tile.

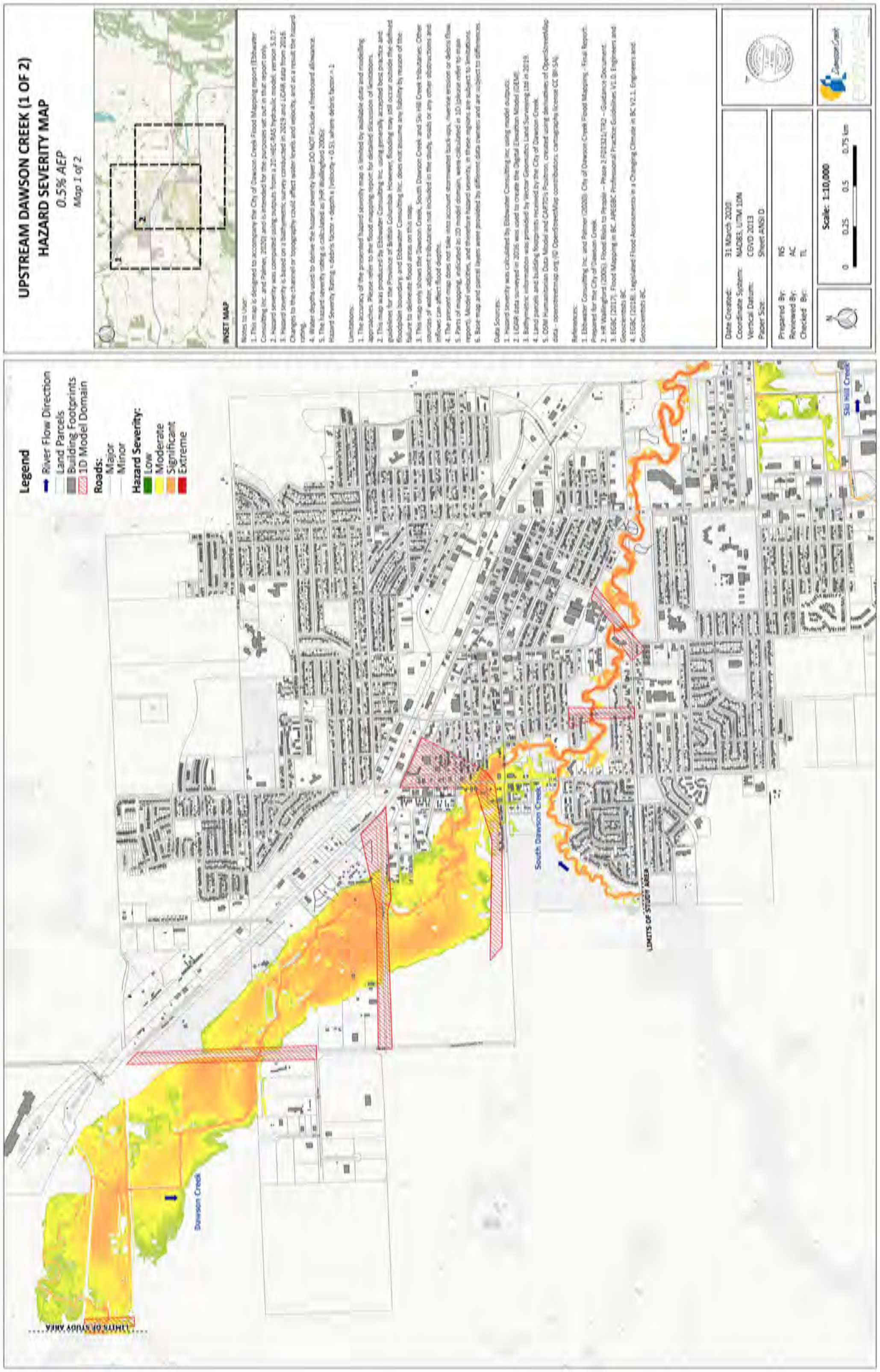

Figure 32: Example hazard severity map for the 0.5% AEP flood (existing conditions) for Upstream Dawson Creek map tile.

7.5 Limitations

As detailed in Section 4, a high-resolution DEM was created for this project. It formed the basis for hydraulic modelling, whose output was used to produce the flood maps. Section 6.6 listed limitations concerning the hydraulic modelling. This section expands on limitations and uncertainties related to the DEM that should be considered when using the flood maps.

The DEM was based on merging LiDAR and bathymetric data. These data were collected in 2016 and 2019, respectively. Due to changes in the land surface over time (e.g., due to erosion, sediment accumulation, construction, etc.), the accuracy of these datasets is continuously diminished. This is important when considering flood map results for the short-term, and especially the long-term under climate change (see Section 5.6 for a description of the uncertainties in the hydrologic analysis related to climate change).

The DEM used as the basis for flood mapping used the Canadian Geodetic Vertical Datum of 2013 (CGVD2013). The field bathymetric data collected used the Canadian Geodetic Vertical Datum of 1928 (CGVD28). For the area of Dawson Creek, the difference between the two datums ranges from +0.04 m to +0.07 m. The range of difference is within the accuracy of the LiDAR data (-0.065 m to +0.075 m), therefore a smooth merging of the two datasets was possible. Note that vertical datum conversion can introduce error and thus was not conducted.

In order to produce flood hazard maps, flood depths were categorized into depth bandings, typically of 1 m. A greater resolution was used for smaller depths to better show the variation in initial flood levels. However, some of the detailed variation in levels is not shown in the maps.

Notwithstanding the limitations discussed above, the results of this work provide a detailed picture of flood hazard in the City of Dawson Creek and will be useful for short- and long-term planning, as well as future risk assessment and mitigation activities.

8 Supporting Hazard Assessments

The overland flood hazard is the focus of this work. However, there are important linkages between flood hazard and fluvial geomorphology hazards, as well as potential impacts on the stormwater drainage system. Field and desktop-based assessments were conducted to better understand these linkages. The field work for these two areas of study was conducted simultaneously on 19-20 August 2019. The full assessments are found in Appendix E and Appendix F, respectively. The following sections summarize the objectives and high-level findings from each.

8.1 Fluvial Geomorphology

Fluvial geomorphological processes along the watercourses within the City are driven by a combination of natural adjustments along meandering watercourses and historical and human-caused alterations to channel morphology. Geomorphological change (e.g., bank erosion, channel avulsion) can occur suddenly, over the course of a single flood event, and have lasting impacts on the landscape. A fluvial geomorphological assessment of Dawson Creek and its tributaries within the City limits, including detailed geomorphology mapping, was completed to document historical and recent trends in floodplain processes and forecast the limits of future erosion hazards associated with flood events.

The overall objective of the fluvial geomorphology assessment was to proactively manage erosion hazards within the City through several steps:

- Documentation of historical changes along the subject watercourses (both natural and human-caused).
- Identification of areas of existing and future erosion.
- Determination of the impacts of existing and proposed road crossings on fluvial geomorphological processes.
- Recommendation of strategies for improved control and management of erosion.
- Prioritization of sites warranting follow-up, site-specific investigation, and possibly mitigation.

The full assessment report (including map book), completed by Palmer, is found in Appendix E. The assessment's geomorphological context, channel overlay analysis, and identified key drivers of morphological change are summarized in the sections below.

8.1.1 Geomorphological Context

In the area of Dawson Creek, the existing morphological form and function of creek channel environments are firstly a result of a complex interaction of geomorphological, hydrological, and geological processes. They also reflect flood management, flow alteration, and channel realignment in association with the growth of the City over the last 50 years. The project area's main channels have incised into the erosion-prone, fine-grained sediments (sand, silt, and clay) deposited on the bottom of a glacial lake on underlying clay-rich till. The amount of incision along the channels is driven by the local thickness of the original lake sediments, the energy available to entrain and transport coarser-grained, till-derived sediments from upstream, and the history of channel modification.

Long-term incision has formed a well-defined valley along Dawson Creek downstream of its confluence with South Dawson Creek, especially as it approaches Pouce Coupé River. These slopes are commonly unstable and susceptible to landslides (e.g., rotational/retrogressive slumps) in response to minor increases in water content and/or over-steepening from fluvial erosion. Widespread landslides along the valleys of Dawson Creek and its major tributaries are likely to continue for millennia, until slopes reach a stable morphology. Points of contact between the irregularly meandering channel and the valley walls influence channel morphology and erosional processes through their confinement and contribution of sediment, which gets transported downstream in suspension or as bed material load.

8.1.2 Channel Overlay Analysis

The channel overlay analysis documented wide-spread human-caused channel realignment and straightening of Dawson Creek prior to 2005 (Table 21). Most notably, this realignment/straightening occurred from Reasbeck Rd. downstream to the Ski Hill Creek confluence between 1959 and 1984. Relative to the anthropogenic realignment/straightening, natural channel avulsions had a smaller impact on the planform and profile of Dawson Creek. Comparatively little anthropogenic realignment/straightening occurred after 2005. The total amount of natural avulsions between 1959 and 2005 (8) is comparable to the total amount of natural avulsions between 2005 to 2019 (7) despite the marked difference in elapsed time. The increase in avulsion frequency since 2005 could be a result of increased channel instability as a result of human-caused activity (realignment, straightening, localized armouring), altered flow regime due to climate and land use change, and/or morphological restructuring downstream of 8th St. following the 2016 flood. The majority of natural avulsions have occurred downstream of 8th St.

Table 21: Number of natural channel avulsions and human-caused realignment/straightening through time.

Time Period	No. of Natural Avulsions	No. of human-caused Realignments/Straightening
2016 to 2019	4	1
2005 to 2016	3	2
1984 to 2005	1	10
1970 to 1984	3	12
1959 to 1970	4	20

Due to widespread human-caused realignment/straightening, most notably in the upper reaches, the channel length from Dangerous Goods Route downstream to the Dawson Creek Transfer Station has decreased from 18,035 m in 1959 to 12,395 m in 2019 (Table 22), a 31.3% loss of channel length. The decrease in channel length has significantly reduced channel sinuosity and correspondingly increased channel slope. This pronounced shortening and steepening alters natural fluvial processes (e.g., sediment recruitment, planform progression, channel incision) and greatly influences flood conveyance and routing. Figure 33 shows the historical channel migration for a section of the Dawson Creek upstream from South Dawson Creek.

Table 22: Channel length of Dawson Creek from Dangerous Good Route downstream to the Dawson Creek Transfer Station through time.

Year	Channel Length (m) DGR to Dawson Creek Transfer Station
2019	12,395
2016	12,577
2005	12,765
1984	13,341
1970	15,065
1959	18,035

Figure 33: Historical channel planforms of Dawson Creek, upstream of the South Dawson Creek confluence.

South Dawson Creek has remained relatively undisturbed over the period of record. Within the study limits, it has an irregularly meandering planform within a heavily forested valley bottom. Numerous woody debris jams influence bed morphology and planform evolution. Relative to Dawson Creek, South Dawson Creek is morphologically stable and has established a dynamic equilibrium. Ski Hill Creek has been extensively realigned/straightened and armoured over the period of record, which has negatively impacted sediment transport, and erosional and depositional processes.

Erosion hazard zones were delineated for the 24 meanders along Dawson Creek and 4 meanders along South Dawson Creek that exhibited systematic migration in recent decades. Furthermore, 15 potential avulsion sites were documented along Dawson Creek, and 12 sites were documented along South Dawson Creek. No erosion hazard zones or potential avulsion sites were identified along Ski Hill Creek due to extensive straightening and hardening of the channel. The locations and extents of erosion hazard zones and potential avulsion sites are illustrated in the geomorphology map book (see Appendix E, Palmer), which is an important deliverable of this project. Examples of the map book for different sections of project area's main channels are shown in Figure 34.

Figure 34: Examples from the fluvial geomorphology map book in Appendix E for the 102nd Ave. area of the Dawson Creek (left) and the 8th St. Bridge crossing (right). In the insets, erosion hazard zones are shown in red (0 to 3 years), orange (3 to 10 years), and yellow (10 to 25 years). Black diamonds on the channel depict zones of human-caused channel confinement. The various coloured lines show channel migration over time.

8.1.3 Key Drivers of Morphological Change

The following are key drivers of morphological processes and change along watercourses within the City:

- **Straightening/Realignment.** From Reasbeck Rd. downstream to the Ski Hill Creek confluence, historical human straightening/realignment have significantly altered natural geomorphological processes and have hindered natural planform development. The impacts of natural meander migration or channel avulsion are greatly overwhelmed by the historical human-constructed straightening/realignment.
- **Large Woody Debris.** Accumulation and jams of large woody debris have influenced bed morphology and planform development and induced natural channel avulsions throughout South

Dawson Creek. The influence of large woody debris is less pronounced, although still notable, along Dawson Creek.

- **Valley Wall Contact.** Downstream of the South Dawson Creek confluence, points of contact between the irregularly meandering Dawson Creek and the well-defined valley walls influence channel morphology and erosional processes through their confinement and contribution of sediment, which gets transported downstream in suspension or as bed material load. These slopes are commonly unstable and susceptible to landslides in response to minor increases in water content and/or over-steepening from fluvial erosion.
- **Road Crossings.** Undersized culverts beneath road crossings have negatively impacted natural geomorphological processes along Dawson Creek, South Dawson Creek, and Ski Hill Creek. In particular, culvert crossings narrower than the bankfull channel width have promoted upstream sediment deposition (i.e. aggradation), due to backwater effects during floods, and compromised planform development. Erosion and rapid channel incisions are common downstream consequences. These morphological effects are evident in association with the 8th St. and 102nd Ave. crossings of Dawson Creek and the 108th Ave. and 18th St. crossings of South Dawson Creek. Bridges and open-bottom culverts that span the bankfull channel width allow the channel to naturally adjust laterally and vertically through the crossing. Bridge crossings at 15th St. and 10th St. have improved the geomorphological function of Dawson Creek.

8.1.4 Summary and Potential Actions

Understanding the dynamic and nature of watercourses in the City of Dawson Creek is critical to managing flood hazard. The historical changes that humans have made along the watercourses have greatly impacted geomorphological processes, as well as flood conveyance and routing. Perturbed geomorphological processes could damage assets located near hazard zones. The following actions should improve the hydraulic and ecological function of the watercourses, and reduce hazard areas (see Appendix E for details):

- Avoid or minimize new channel realignments.
- Restore channel length.
- Complete a landslide hazard assessment.
- Re-establish riparian vegetation.
- Apply zoning and planning tools.
- Replace undersized culverts.

8.2 Stormwater Drainage

The objective of this assessment was to determine if there are specific outfalls whose discharge capacities could be impacted by flood flows in the creek, thus affecting the stormwater system. This will enable the City to proactively manage backflow hazards. This assessment was considered relatively minor compared to the other assessments in this project.

The assessment included broader field work components that included a channel condition survey to identify obstructions to other key assets interfacing the project area's main channels (e.g., infrastructure bridges and culvert crossings, and water level gauging stations). The information gathered from the broader field survey was useful for the hydrology and hydraulic modelling tasks.

The objective of identifying outfalls with compromised capacities was addressed through the following tasks:

- Conduct a field survey to visit and document the infrastructure and channel conditions at select outfall locations.
- Using flood water level and extent results from the hydraulic model runs for various AEP flood events (Section 6.5), identify outfalls that are flood prone.
- Based on the priority outfall locations, run the stormwater drainage system model to provide a high-level indication of potential backflow hazard locations.

The full assessment report, including the field survey, is found in Appendix F. The assessment's key findings related to outfalls with compromised flow capacities are summarized in the sections below.

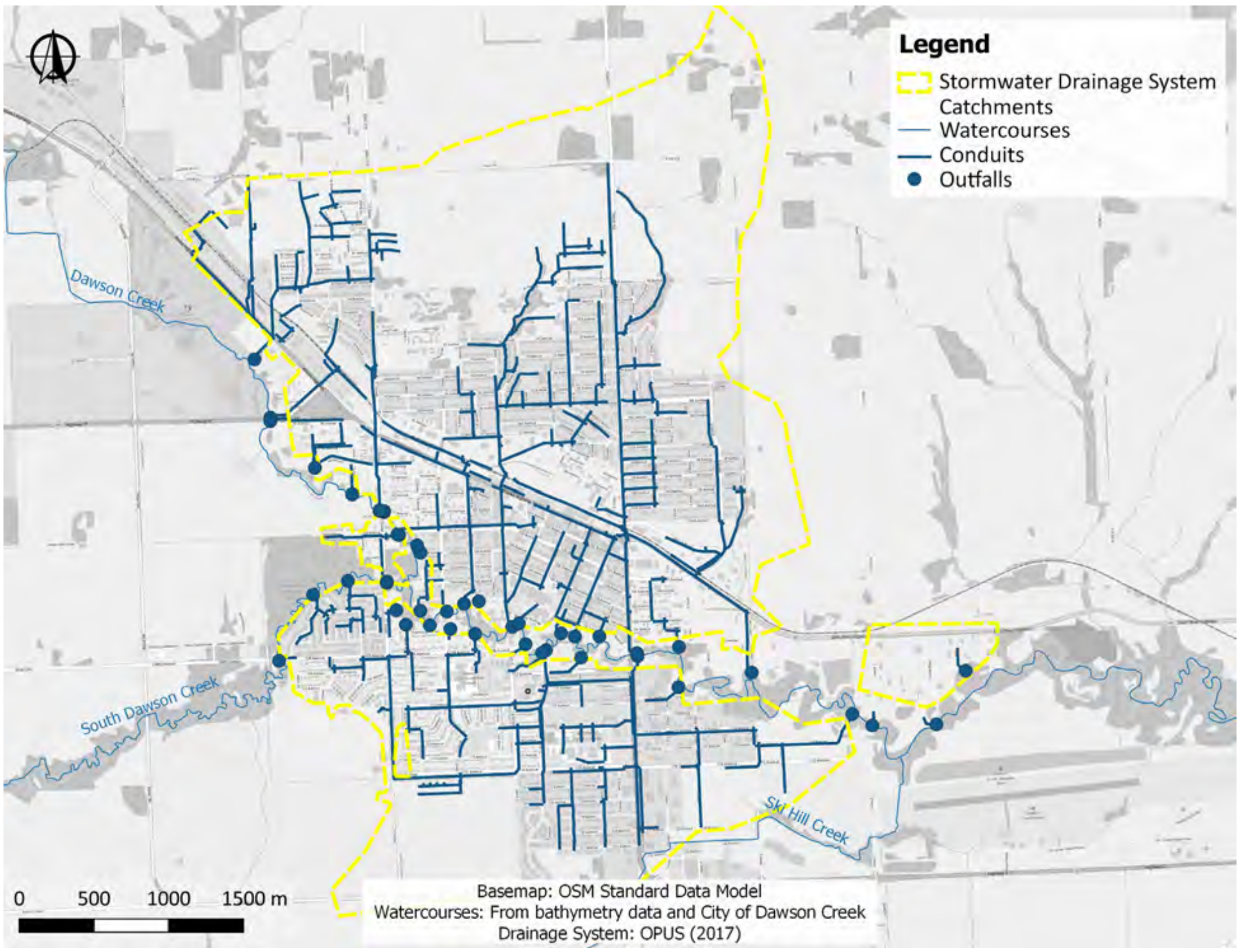

Figure 35: Stormwater drainage assessment boundary.

8.2.1 Drainage Model

Dawson Creek's urban stormwater drainage system comprises collection and conveyance infrastructure such as culverts, stormwater mains, roadside ditches, catch basins and inlets, and stormwater maintenance holes. This infrastructure conveys stormwater to 79 outfalls; 46 outfalls discharge to the project area main channels. A stormwater model of the drainage system was developed for the purpose of developing the *Drainage Master Plan* (OPUS, 2017). The drainage model was constructed in the Computational Hydraulic International's PCSWMM software and was shared with the project team by the City of Dawson Creek. The existing model assumes free flow conditions at all the outflows; this is the main assumption tested in the analysis below.

8.2.2 Outfalls with Compromised Flow Capacities

We conducted a review of the 46 outfalls to identify those that could be impacted by riverine flood levels causing issues in the stormwater network. Outfalls are likely to become impacted by riverine flood based on the point at which creek water levels rise above the invert of the outfall. This impact will worsen as water levels increase therefore increasing the hydraulic head. This could lead to the outfall causing backflow in "upstream" areas of the piping network.

To identify priority outfalls, screening criteria were developed to consider key factors as follows:

- Outfalls that served significant upstream drainage networks. This screening was based on professional judgement.
- Outfalls whose capacity would be compromised by lower-magnitude flood events (10% to 50% AEP events). This was based on flood information extracted for the 46 outfall locations using the HEC-RAS hydraulic model software (Section 6), for all existing condition scenarios.

A plot was produced showing the lowest flood magnitude event at which outfalls become affected (Figure 36). This was completed based on the flood elevations extracted from the riverine hydraulic model software (HEC-RAS 2D)[17] and the invert elevation of the outfall, obtained from the stormwater drainage model (PCSWMM)[18]. Figure 36 to Figure 38 are included in the Flood Hazard Map Atlas (Appendix D).

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[17] The water levels used were the maximum flood levels for each scenario modelled at these locations. Therefore, they represent a snapshot in time of the worst-case condition during each scenario.

[18] The vertical datum for the invert elevations was not explicitly stated in the OPUS (2017) report, and staff at the City of Dawson Creek could not confirm it. Assuming the vertical datum is either CGVD28 or CGVD2013, the uncertainty in invert elevations is between +0.04 m and +0.07 m. This uncertainty is reasonable for this high-level analysis. However, the stormwater drainage system model datum should be confirmed for future studies.

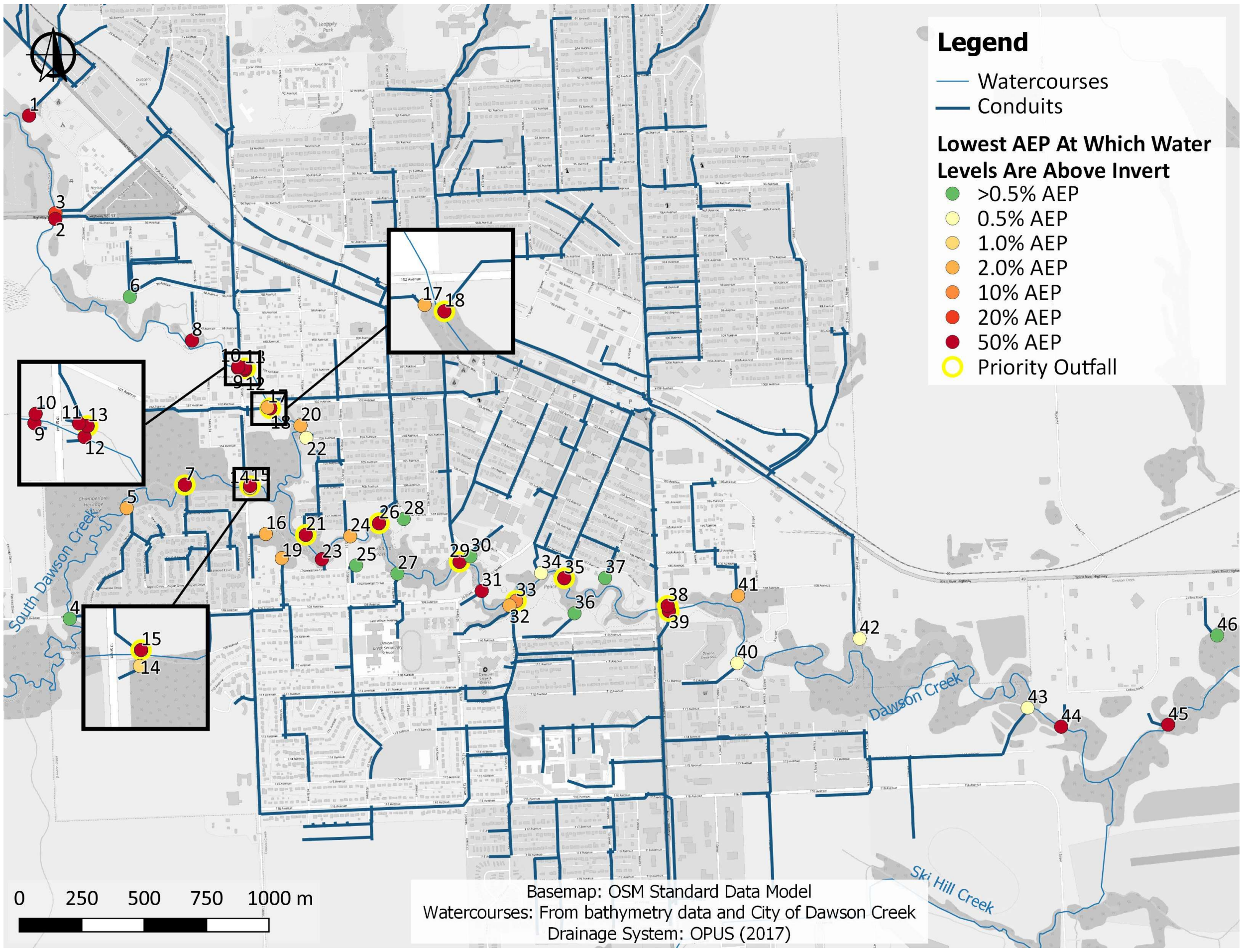

Figure 36: Analysis of outfalls impacted by different AEP events.

Based on this screening analysis, 11 priority outfalls were identified (Table 23) (see Appendix F for details on this analysis). It should be noted that the likelihood of a backflow and associated flooding occurring is dependent on several factors. This includes the geometry of the drainage network, and land and water levels in the urban environment, which were not considered.

Table 23: Priority outfalls based on professional judgement and flood information from the hydraulic model.

Outfall Number	Outfall Name	Outfall Diameter (m)	Approximate Area Drained
7	OU162051	1.05	Willowbrook Crescent & 18th St north of 108th Ave
13	OU15401	0.90	17th St. north of 102nd Ave.
15	OU153221	0.90	17th St. north of South Dawson Creek
18	OU154001	0.675	102nd Ave. east of Dawson Creek
21	OU153121	0.45	102nd Ave. & 16th St. south of 104th Ave.
26	OU153151	1.20	14th St. from Alaska Highway to 107th Ave.
29	OU152061	0.75	13th St. north of Dawson Creek
33	OU101001	0.60	12th St. to 118th Ave.

Outfall Number	Outfall Name	Outfall Diameter (m)	Approximate Area Drained
35	OU152021	0.90	9th St. north of Dawson Creek to Alaska Highway
38	OU114002	0.525	8th St. north of Dawson Creek to Alaska Highway
39	OU114011	1.20	8th St. south of Dawson Creek to 121 Ave.

The list of outfalls in Table 23 was checked against areas of the stormwater drainage system that were modelled in the *Drainage Master Plan* (OPUS, 2017) as being surcharged during the design storm (20% AEP, over a 24-hr period). Based on Figure 7-1 of (OPUS, 2017), all of the outfalls listed in Table 23 are part of surcharged stormwater mains. This analysis suggests that the pluvial flood conditions modelled as causing surcharging in specific areas of the stormwater drainage system are likely to be exacerbated due to riverine flood conditions.

8.2.3 Impact to Outfalls

To gain a better understanding of the magnitude of impact on the stormwater drainage system an analysis was done of the depth of water above outfall inverts (or head level) for the low (20% AEP) and very high (0.5% AEP) magnitude flood events. The results are presented in Figure 37 and Figure 38, respectively. As presented in these figures there are significant head levels across a number of the priority outfalls for even the low magnitude flood event (20% AEP). For this low event, Outfalls 7, 13, 18, 26, 29, 35, and 39 all have head levels of more than 2.0 m. For the very high event (0.5% AEP), the head levels increase dramatically, with most outfalls experiencing downstream head levels of over 2.0 m. This means that there is the potential for backflow from a much larger number of outfalls than those identified as priority.

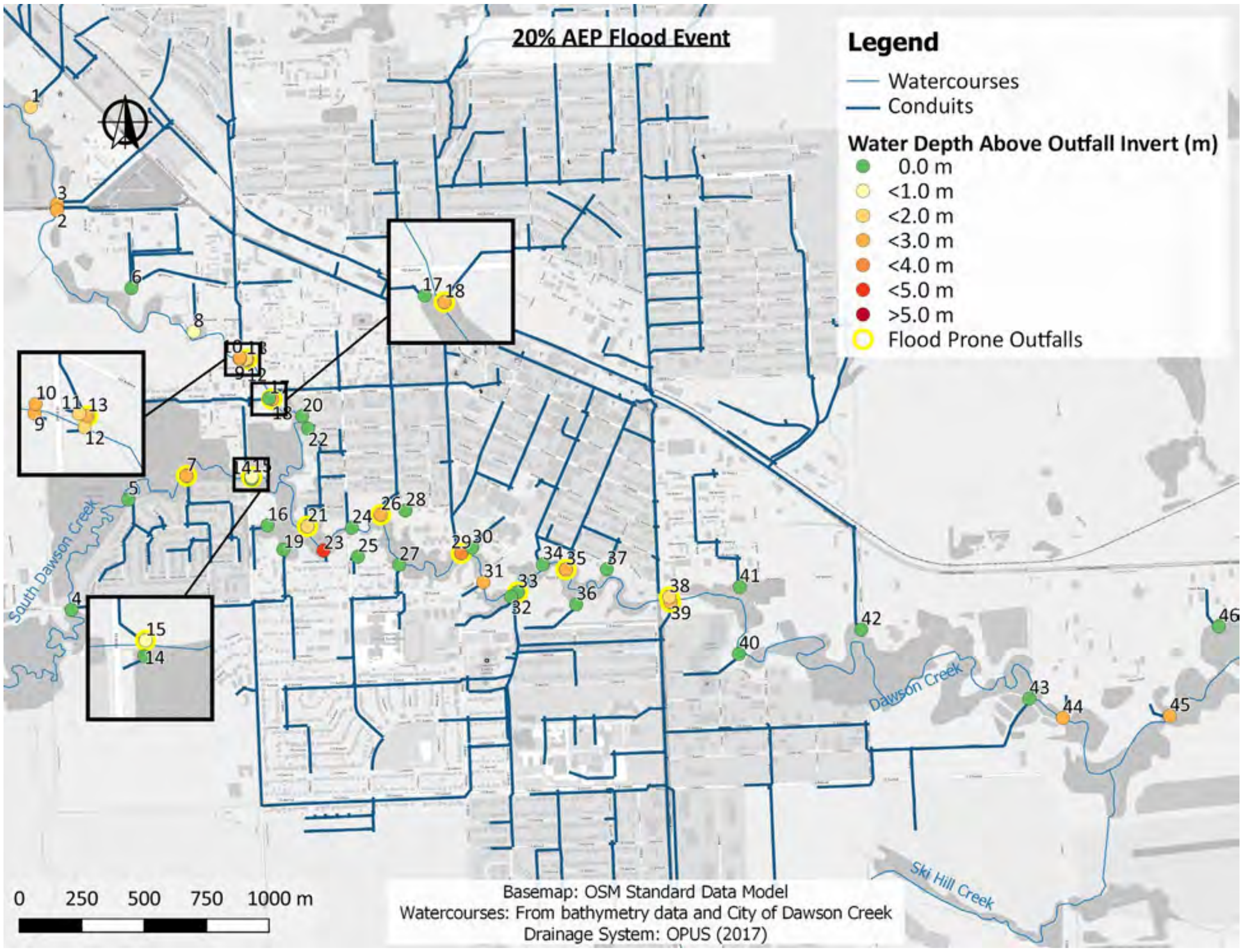

Figure 37: Depth of head water at outfalls for a low magnitude flood event (20% AEP).

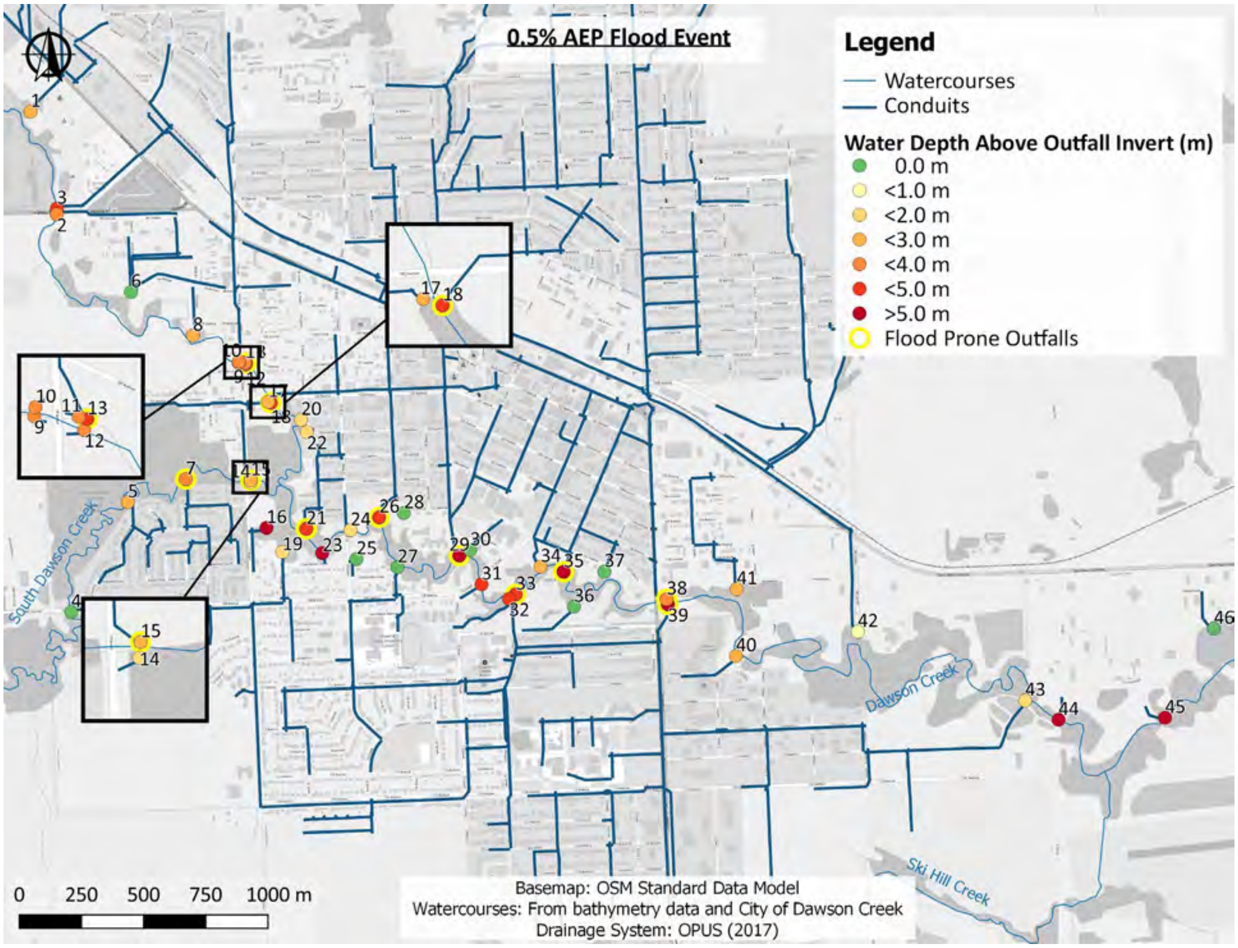

Figure 38: Depth of head water at outfalls for a very high magnitude flood event (0.5% AEP).

8.2.4 Drainage Model Runs

The PCSWMM model was run for the 10 outfalls of concern to visualize the effect during a low magnitude riverine flood event (20% AEP) and the design storm rainfall event (20% AEP, over a 24-hour period). Figure 39 illustrates this impact for Outfall 29, as an example. The figure shows where overflow and backwater would occur in the drainage system. This occurs because the outfall's discharge capacity is eliminated due to high flood water levels in the Dawson Creek channel.

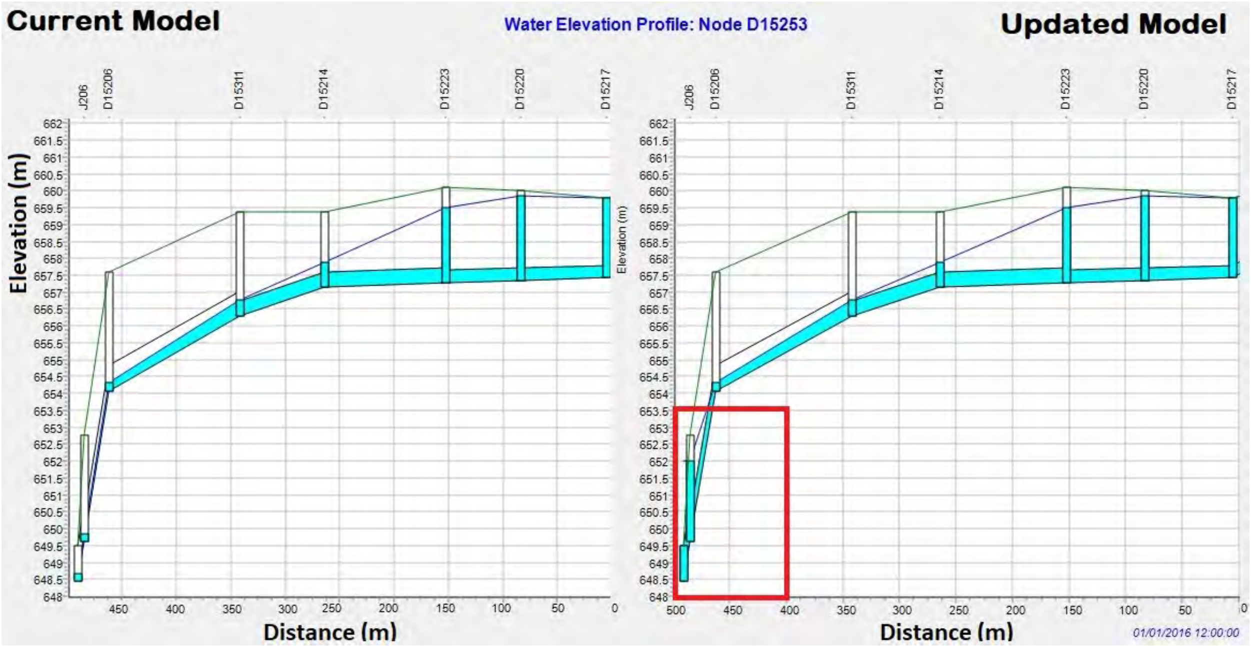

Figure 39: Illustrative example of potential overflow and backwater conditions in the upstream drainage system of Outfall 29. The current model (left) only considers the design rainfall event (20% AEP, over a 24-hour period). The updated model (right) considers the design rainfall event and riverine flooding (20% AEP). Water appears turquoise colour, the ground surface is green colour, and the vertical rectangles are maintenance holes.

8.2.5 Summary and Potential Actions

The discharge flow capacity of key stormwater outfalls can be compromised during riverine flood conditions, which can affect upstream areas in the stormwater drainage system. These linkages need to be considered within the City's efforts to mitigate urban flooding from pluvial events, including:

- Update downstream boundary conditions in the stormwater drainage model (PCSWMM) to simulate backflow conditions during various AEP floods.
- Prepare and implement plans to manage backflow during flood events.
- Prioritize maintenance or replacement of the priority outfalls identified in Table 2 to ensure that they are in good working condition.
- Revisit flood impacts based on infrastructure projects that could affect creek channel dynamics.

8.3 Summary of Supporting Hazard Assessments

The project area's main channels include important interfaces with fluvial geomorphological processes and urban stormwater outfall infrastructure. The extensive human-constructed straightening and realignment of the Dawson Creek channel has led to increased flood conveyance and routing. Such conditions have created erosion hazards and channel avulsion zones. These effects need to be considered from a watershed perspective within the City's flood mitigation efforts.

The hazards related to fluvial geomorphology and stormwater drainage that have been identified in this section are driven by riverine flooding. As the influences of climate change increase, so will the processes and conditions that create these hazards.

9 Evaluation of Structural Mitigation Options

The hydraulic model, as described in Section 6, was set-up to explore flood hazard under various flow and climate change scenarios under existing channel and crossing configurations. The hydraulic model offers an opportunity to also explore how flood hydraulics are affected under "what if" scenarios. It was applied to explore 3 mitigation options that have previously been considered by the City. These options do not represent all possible options, and certainly do not represent non-structural options that will reduce flood risk. The intent of this investigation is to explore whether or not the three structural options have merit from a hydraulic perspective only, and should be considered as a screening-level assessment.

The goal was to identify a preferred approach that would decrease flood hazard, particularly in the area of the 102nd Ave crossing, where flood damages have been great in recent years. The implementation concepts for each option, and their reference names for this section, are summarized below:

- **Option 1 – Upgrade.** Increase flow capacity by reducing the constriction caused at the 102nd Ave. crossing.
- **Option 2 – Storage.** Attenuate peak flows at the 102nd Ave. crossing by storing water at an upstream location.
- **Option 3 – Combination.** Combine the concepts from Options 1 and 2.

The conceptual-level evaluation compared different model runs, and their resulting effects in the vicinity of the 102nd Ave. crossing. The options were evaluated from hydraulic and fluvial geomorphology perspectives. The methods and results for each discipline are discussed separately, then the analyses are integrated within the context of a preferred approach.

For the reader's benefit throughout this section, flood events are described in terms of their relative flood magnitude. This is shown in Table 24, which is an abridged version of the information in Table 16 (Section 6.5).

Table 24: Linking the annual exceedance probablity events modelled for this project with relative flood flow magnitudes (corresponding indicative return periods and likelihoods are shown in Table 17).

Annual Exceedance Probability (AEP) Event Modelled	0.5%	1%	2%	10%	20%	50%
Relative Flood Magnitude	Very high	High	Moderately high	Moderately low	Low	Very low

9.1 Hydraulic Analysis

The hydraulic analysis was based on the model development described in Section 6. Test runs were iterated to consider how variations in the Upgrade and Storage options affected the system hydraulics. The rationale to define the model runs is described in the next section. This is followed by results for each option and a summary of results.

9.1.1 Model Runs Definition

The Upgrade option increased the flow capacity of the two existing circular culverts at 102nd Ave. that currently have a combined cross-sectional area of 10 m^2 (2.2 m and 2.8 m diameter). Two sub-options were defined based on two cross-sectional areas, considering the site's height and width constraints[19]. Upgrade-1 had a cross-sectional area of 24 m^2 (8-m span), or 2.4 times greater than existing conditions. Upgrade-2 had a cross-sectional area of 36 m^2 (12-m span), or 3.6 times greater than existing conditions. These sub-options helped us understand how much difference the incremental increases in cross-sectional area have on flood reduction.

The Storage option had no sub-options. Rather, we determined a minimum storage volume based on the following reasoning. To be effective, we assumed that the volume should be large enough to attenuate a very high flood event (0.5% AEP) such that when those flows reached the constriction at 102nd Ave, the crossing was not overtopped. For existing conditions, the highest flood flows that do not overtop at the 102nd Ave. crossing occur for the moderately low flood event (10% AEP). Based on this reasoning, a minimum storage reservoir size of 9,000 m^3 was determined to be required[20].

The Combination option joined the Upgrade-1 sub-option (8-m span) with the Storage option.

Model runs were conducted for existing conditions, as well as for the 3 options summarized in Table 25. Results for the modelled 2016 flood event (Section 6.3) were also included in specific analyses. This was done to comment on differences between that moderately high to high flood event (1.3% AEP) and existing conditions, which considers upgrades to the 15th St., 10th St., and 8th St.[21].

Table 25: Summary of model runs and input flows.

Model Run	Description	Relative Flood Magnitude (AEP) used in Model Runs
Existing Conditions	Existing conditions at 102nd Ave. with 2 circular culverts having cross-sectional area of 10 m^2.	Low, Moderately low, and Moderately high (20%, 10%, 2% AEP, respectively)
Option 1 – Upgrade	Cross-sectional area increase at 102nd Ave. crossing: • Upgrade-1: 24 m^2 (8-m span) • Upgrade-2: 36 m^2 (12-m span).	
Option 2 – Storage	Upstream storage volume of 9,000 m^3.	Very high (0.5% AEP)
Option 3 – Combination	Apply Upgrade-1 and storage volume.	

[19] The flow capacity increase was constrained by the channel bottom and the top-of-road elevation, which was 3 m. The sub-options were represented functionally in the model as one open-bottom box culvert. This structure is feasible for the 8-m span (Upgrade-1), while the 12-m span (Upgrade-2) would more likely take the form of a bridge. Considering this level of design detail was out of the scope of this conceptual evaluation.

[20] The 9,000 m^3 of storage volume required is equivalent to the volume of about three-and-a-half Olympic-size swimming pools. The location of the reservoir was undetermined for this level of study.

[21] While the 8th St. crossing upgrade is not yet complete, it was included in the existing conditions model runs.

9.1.2 Upgrade Option Results

For the Upgrade-1 run, the maximum flood extent at 102nd Ave. decreases substantially for the moderately high flood event (2% AEP), compared to existing conditions. This reduction is clear in Figure 40 (left, compare turquoise and navy colours). Further, the left image in Figure 40 shows that the 102nd Ave. crossing is not overtopped for Upgrade-1[22]. Figure 40 (left) also provides insights into the flood reduction benefits from crossing upgrades that have occurred since the 2016 improvements (compare the navy and red colours). Figure 40 (right), shows flood extents for the moderately low flood event (10% AEP). The figure shows a relatively small amount of backflow caused at the 102nd Ave. constriction under Upgrade-1 (8-m span) versus Upgrade-2 (12-m span).

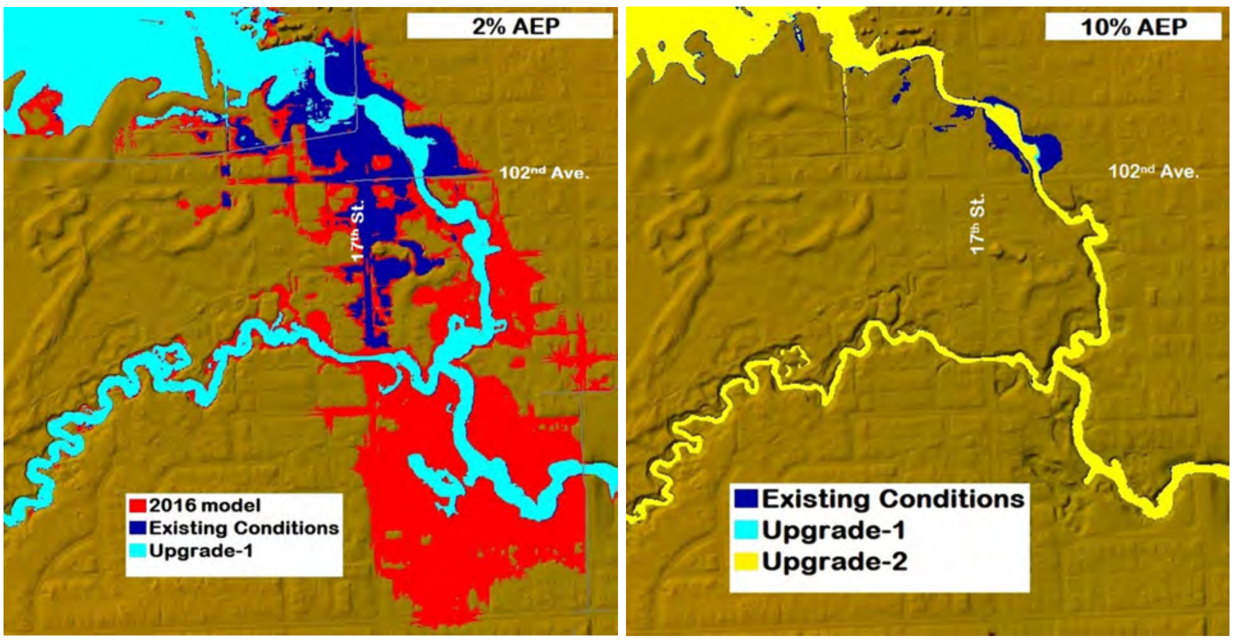

Figure 40: Maximum flood extent comparison for the Existing Conditions, Upgrade, and 2016 modelled flood runs.

Considering that the 102nd Ave. crossing area is complex, we also analyzed the effects of the Upgrade runs on water surface elevations. These are shown for the 17th St. Bridge crossing, located approximately 200 m upstream of the 102nd Ave. crossing.

While the 102nd Ave. crossing is not overtopped under both Upgrade runs under the moderately high flood event (2% AEP) (Figure 40), flows *do* overtop at the 17th St. Bridge for that event. This occurs despite a water surface elevation decrease of approximately 0.6 m at the 17th St. Bridge crossing, as modelled just upstream from the crossing (Figure 41). This demonstrates that while the Upgrade options may result in improvements at the 102nd Ave. crossing, these are localized and should be considered in a wider context. This is shown in water surface elevation comparisons for major crossings upstream and downstream in Table 26.

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[22] Based on both images in Figure 40 it can be deduced that both Upgrade option runs do not overtop at the 102nd Ave. crossing under the moderately high flood event (2% AEP).

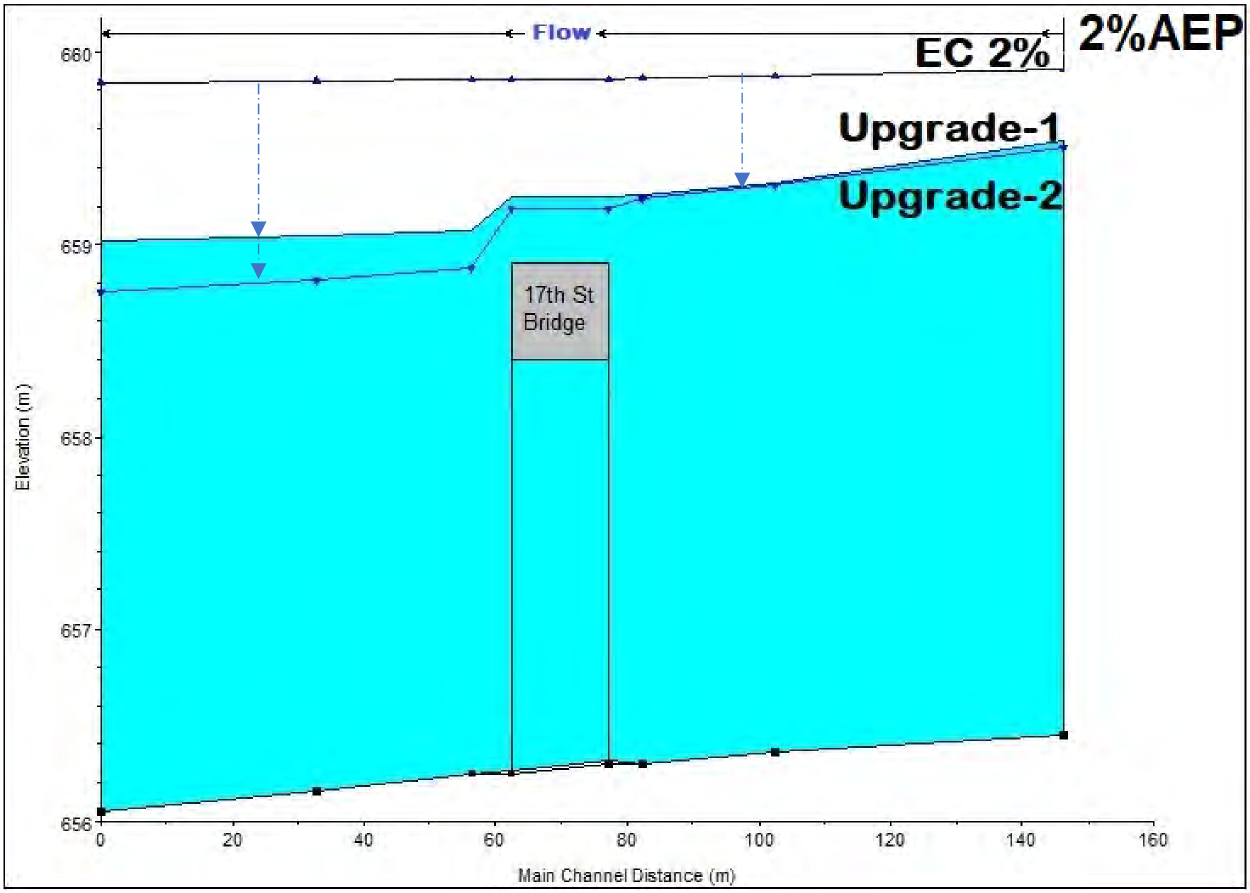

Figure 41: Water surface profile comparison of Existing Conditions (EC) and Upgrade runs for the moderately high flood (2% AEP) at the 17th St. Bridge. The downward arrows show the mitigation effects of the sub-options, upstream and downstream of the crossing.

For the moderately low flood event (10% AEP), the 17th St. Bridge is overtopped under existing conditions for both Upgrade runs (Figure 42). Compared to existing conditions, the Upgrade-1 water levels decrease by approximately 0.2 m at 17th St. Bridge and 0.8 m at the 102nd Ave. The water surfaces decrease slightly more at both crossings for Upgrade-2, which is expected given the larger cross-sectional area (36 m^2). For the lower flood events (e.g., 20% AEP), water surfaces decrease even more for both Upgrade runs, and both crossings are cleared under existing conditions as well as both Upgrade runs.

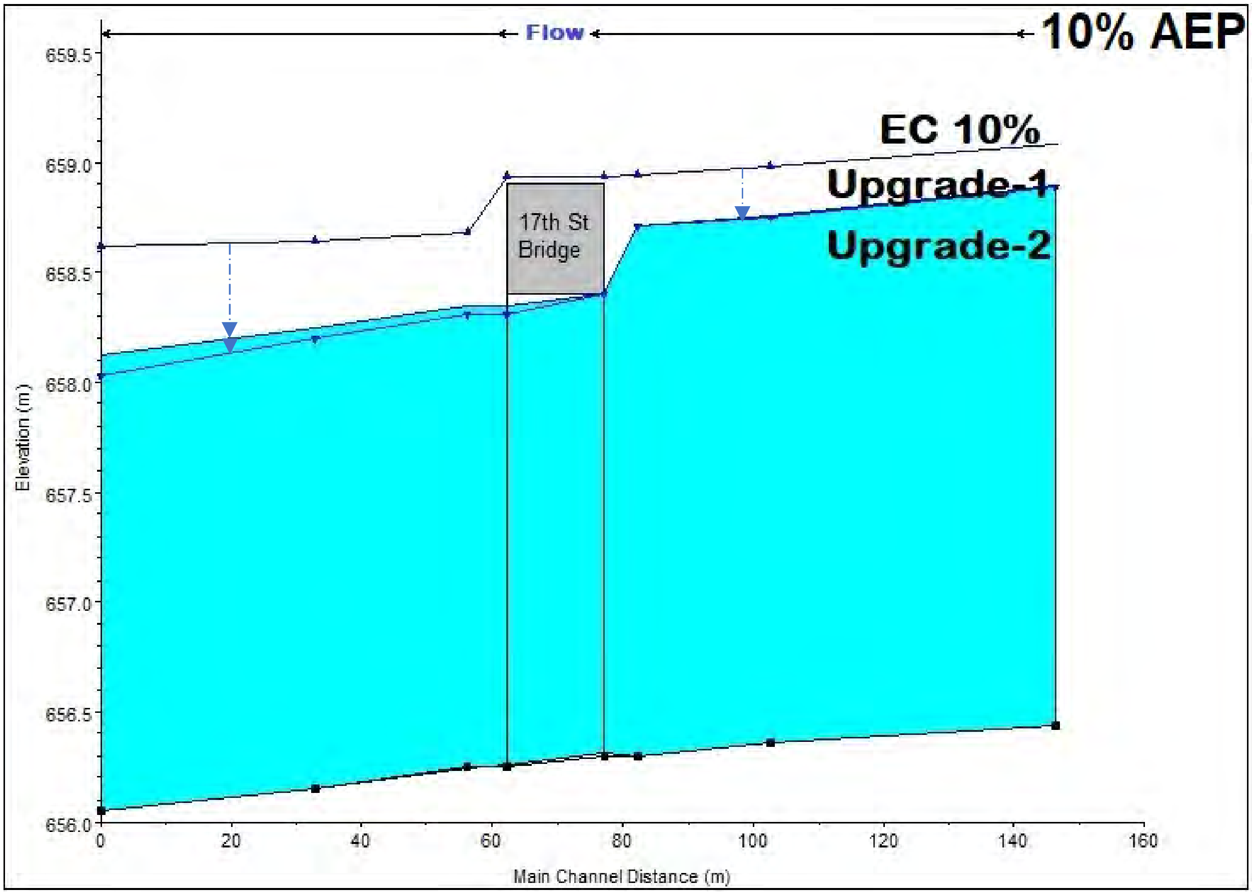

Figure 42: Water surface profile comparison of Existing Conditions (EC) and Upgrade runs for the moderately low flood (10% AEP) at the 17th St. Bridge. The downward arrows show the mitigation effects of the sub-options, upstream and downstream of the crossing.

Table 26 compares the Upgrade runs for moderately high and moderately low magnitude floods (2% and 10% AEPs, respectively). For the moderately high flood (2% AEP) for both Upgrade runs there is no overtopping at the 102nd Ave. crossing. However, as shown in Figure 41, under the same run the 17th St. Bridge is overtopped (see bold numbers). Table 26 also shows that the flood benefits resulting from the Upgrade options are localized. There are no changes at crossings located upstream from 17th St. Bridge, and water surface elevations increase slightly at downstream crossings.

For the moderately low flood (10% AEP), overtopping that occurs at the 17th St. bridge under existing conditions is eliminated under both Upgrade options (also shown in Figure 42). The upstream and downstream flood benefits resulting from the Upgrade options are even smaller compared to the 2% AEP flood.

Table 26: Water surface elevations for Upgrade-1 and Upgrade-2 runs compared to Existing Conditions under moderately low (10% AEP) and moderately high floods (2% AEPs).

Crossing	Water Surface Elevation (m) Moderately high flood			Water Surface Elevation (m) Moderately low flood		
	Existing Conditions (2% AEP)	Change with Upgrade-1	Change with Upgrade-2	Existing Conditions (10% AEP)	Change with Upgrade-1	Change with Upgrade-2
Dawson Creek						
223 Rd.	666.4	0.0	0.0	666.0	0.0	0.0
Dangerous Goods Route	662.6	0.0	0.0	662.3	0.0	0.0
John Hart Highway	660.8	+0.1	+0.1	660.2	0.0	0.0
17th St.	659.9[1,2]	-0.6[2]	-0.7[2]	658.9[1,2]	-0.2	-0.2
102nd Ave.	659.8[2,3]	-1.1	-1.5	658.5[3]	-0.8	-1.0
Downstream from South Dawson Creek Confluence						
15th St.	655.4	+0.1	+0.1	654.6	0.0	0.0
10th St.	652.5	+0.0	+0.1	651.7	0.0	0.0

Note 1: The crossing does not overtop for water surface elevations lower than 658.8 m.
Note 2: The crossing is overtopped.
Note 3: The crossing does not overtop for water surface elevations lower than 659.6 m.

9.1.3 Storage and Combination Option Results

Compared to the Upgrade options, the Storage and Combination options simulated the attenuation of the peak of a very high magnitude flood event (0.5% AEP). The results cannot easily be compared with the Upgrade options. However, the effectiveness of Uprade-1 can be evaluated within this set of options, as it is included within the Combination run.

Figure 43 compares the Storage and Combination options for existing conditions under the very high (0.5% AEP, left) and moderately high (2% AEP, right) flood events. For both of these events, the maximum flood extent at 102nd Ave. decreases substantially compared to existing conditions for both option runs (Figure 43, both images). As expected, the flood extent for the Combination run is smaller compared to the Storage run. This is due to the additional benefit of the larger cross-sectional area at the 102nd Ave. crossing. Without the increased cross-sectional area at 102nd Ave. for the Storage run, the constriction causes backflow (Figure 43, both images). However, the Storage run does not cause the 102nd Ave crossing to be overtopped.

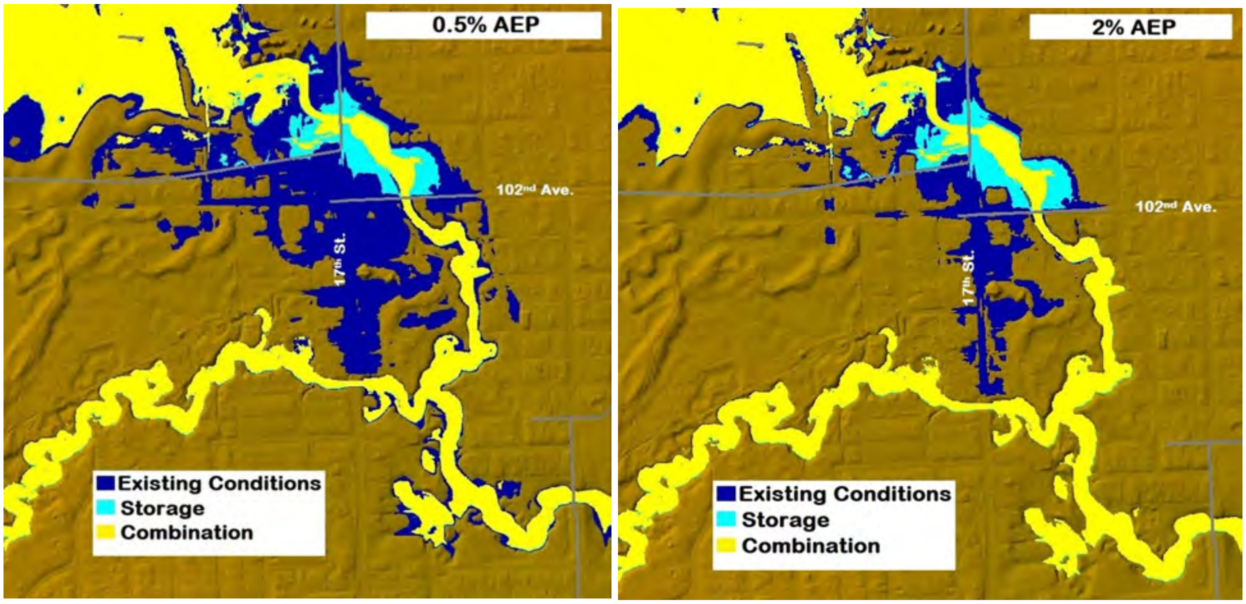

Figure 43: Maximum flood extents for Existing Conditions for very high flood (5% AEP, left) and moderately high flood (2% AEP, right) events compared with Storage and Combination runs. The extents for the Storage and Combination runs are the same in both images.

The water surface profiles for the Storage and Combination runs fall between those for existing conditions under a moderately low (10% AEP) and moderately high (2% AEP) flood event. To understand the flood reduction benefits of the Storage and Combination runs, they are compared with the same very high flood event under existing conditions (Figure 44, compare Storage and Combination lines with EC 0.5% line and shown by the downward arrows). At the 17th St. Bridge, water surface elevations are substantially reduced. However, neither the Storage nor Combination options avoid overtopping at the 17th St. Bridge (despite this being the case at 102nd Ave.[23]). As expected, the water surface elevation for Combination is lower compared to Storage due to the larger flow capacity at the nearby 102nd Ave. crossing.

[23] This is because the Storage and Combination options are based on the upstream reservoir volume of 9,000 m^3, which is equivalent to the size necessary to avoid overtopping at 102nd Ave. only, during a very high flood (0.5% AEP). A larger reservoir would be required to avoid overtopping at 17th St. during the same event.

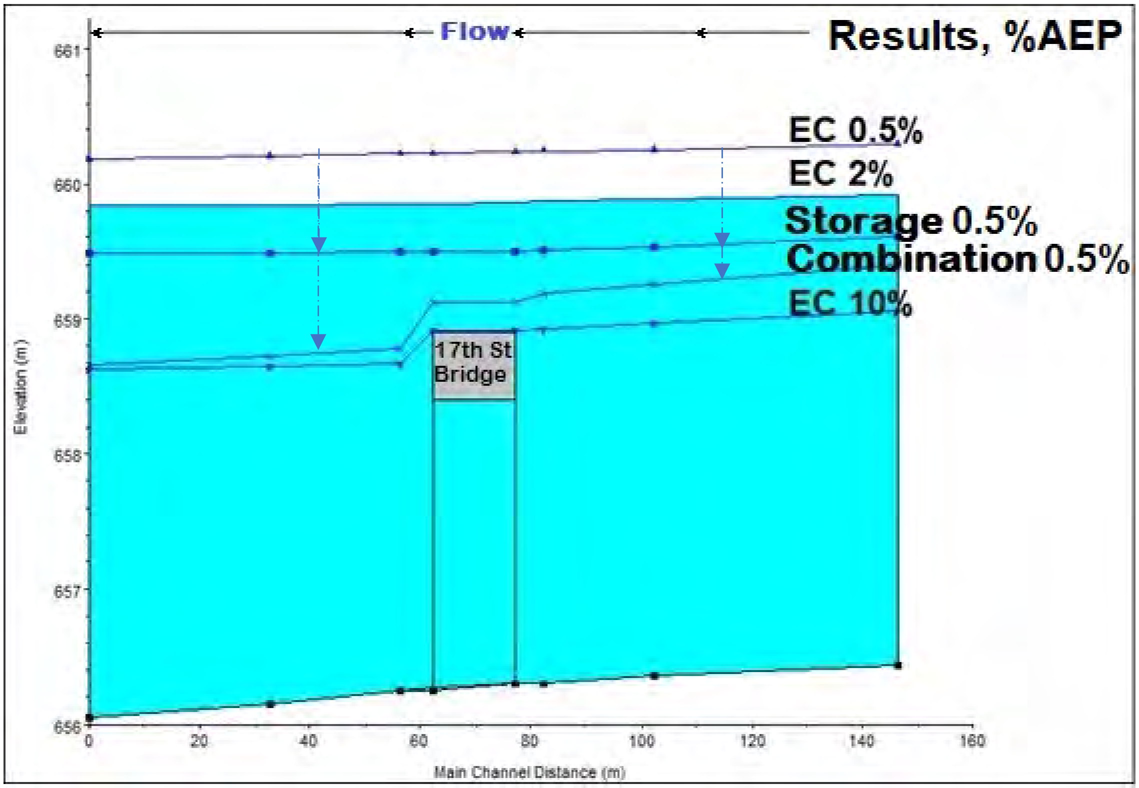

Figure 44: Water surface profile comparison of Existing Conditions, Storage, and Combination runs at the 17th St. Bridge. The downward arrows show the mitigation effects during a very high flood (0.5% AEP), for which these options were modelled.

To obtain a watershed perspective of the effects from upstream storage, Table 27 compares the water surface elevation at major crossings upstream and downstream from the 102nd Ave. area. The table compares the differences in elevations for moderately high (2% AEP) and moderately low (10% AEP) flood events under existing conditions.

Compared to the moderately high flood event (2% AEP) under existing conditions, both the Storage and Combination option runs result in slight reductions in water surface elevation at all major crossings upstream from 102nd Ave (e.g., elevations are reduced by -0.4 m at 223 Rd. for both options). Under existing conditions, both the 17th St. Bridge and 102nd Ave. crossing are overtopped. Comparatively, flows under the Storage and Combination runs cause overtopping at the 17th St. Bridge, but not at the 102nd Ave. crossing. Downstream from 102nd Ave., water surface elevations increase slightly under both Storage and Combination runs.

Compared to the moderately low flood (10% AEP) under existing conditions, the difference in water surface elevations under the Storage and Combination runs are mostly positive. Overtopping occurs at 17th St. under existing conditions as well as under the Storage and Combination runs. At 102nd Ave., overtopping occurs neither under existing conditions nor under the Storage or Combination runs.

Table 27: Water surface elevations for Storage and Combination runs compared to Existing Conditions under 10% and 2% AEPs.

Water Surface Elevation (m)						
Crossing	**Existing Conditions (2% AEP)[1]**	**Change with Storage[2]**	**Change with Combination[2]**	**Existing Conditions (10% AEP)[1]**	**Change with Storage[2]**	**Change with Combination[2]**
Dawson Creek						
223 Rd.	666.4	-0.4	-0.4	666.0	0.0	0.0
Dangerous Goods Route	662.6	-0.1	-0.1	662.3	+0.2	+0.2
John Hart Highway	660.8	-0.3	-0.3	660.2	+0.3	+0.3
17th St.	659.9[3,4]	-0.4[4]	-0.7[4]	658.9[3,4]	+0.6[4]	+0.3[4]
102nd Ave.	659.8[4,5]	-0.3	-0.4	658.5[5]	+1.0	-0.1
Downstream from South Dawson Creek Confluence						
15th St.	655.4	+0.4	+0.4	654.6	+1.2	+1.2
10th St.	652.5	+0.3	+0.3	651.7	+1.1	+1.1

Note 1: The moderately high (2% AEP) and the moderately low (10% AEP) flood events only correspond to the Existing Conditions runs.
Note 2: The storage and combination options are based on the inflow volume of a very high magnitude flood event (0.5% AEP).
Note 3: The crossing does not overtop for water surface elevations lower than 658.8 m.
Note 4: The crossing is overtopped.
Note 5: The crossing does not overtop for water surface elevations lower than 659.6 m.

9.1.4 Summary of Mitigation Effectiveness

The effectiveness of the proposed flood mitigation options is summarized here. This is described using modelling flood depths for key points of interest based on structural crossings of the past (i.e., pre-2016 flood), existing conditions, and the proposed future conditions and by considering the conveyance capacity at the 102nd Ave. and 17th St. crossings.

9.1.4.1 Flood Depths at Points of Interest

Based on the modelled flood extents, Table 28 shows the maximum water depth at the points of interest for a variety of model runs, including the 2016 flood event. The results suggest that the crossing upgrades that have been implemented (or will be implemented soon) since 2016 at 15th St., 10th St., and 8th St. have reduced the likelihood of flooding in the upstream reaches of the Dawson Creek. Additional improvements, represented by the mitigation options, further decrease flood depths at the points of interest.

Table 28: Flood water depths at points of interest under various model runs; zero values mean no flooding

Maximum Water Depth (m)										
Point of Interest	**2016 Flood**	**Existing Conditions**			**Upgrade-1**	**Upgrade-2**	**Upgrade-1**	**Upgrade-2**	**Storage**	**Combination**
	(~1.3% AEP)	Very High (0.5% AEP)	High (1% AEP)	Mod. high (2% AEP)	Very High (0.5% AEP)		Mod. high (2% AEP)		Very high (0.5% AEP[1])	
Golf Course	0.7	1.5	0.8	0.4	1.5	1.5	0.5	0.5	0.3	0.2
Tubby's Trailer Park	0.1	0.2	0.1	0	0.2	0.2	0	0	0	0
17th St. Homes / businesses	0.7	0.8	0.6	0.5	0.7	0.6	0	0	0.1	0
102nd Ave. Homes	0.1	0.2	0	0	0.1	0	0	0	0	0
Funeral Home	0.1	0.2	0	0	0.1	0	0	0	0	0
Note 1: Storage and Combination runs are based on the volume of the 0.5% and include upstream storage. For lower magnitude flood events, there would be no flooding expected at the golf course.										

The effectiveness of potential mitigation can be illustrated by describing the results in Table 28 and using the 17th St. homes/businesses point of interest as an example. During the 2016 event, this area was flooded (it was modelled to be a maximum of 70 cm under water). However, for the same area, flood depths under existing conditions (i.e., with recent and planned upgrades) are modelled to be *lower* (maximum of 60 cm under water) for a *slightly higher* magnitude flood (1% AEP).

The difference between existing conditions and potential mitigation options for this same point of interest is shown when comparing results for the 0.5% AEP flood. During this very high flood under existing conditions, the 17th St. homes/businesses are modelled to be a maximum of 80 cm under water. The effects of Upgrade-1 and Upgrade-2 for this flood reduce water depths to a maximum of 70 cm and 60 cm, respectively. The Storage and Combination options are effective at mitigating flood hazard at the point of interest.

9.1.4.2 <u>Safe Flow Conveyance</u>

It is important to understand the conditions at which flows are safely conveyed through a crossing. Alternately, backwatering and overtopping can occur and lead to unsafe conditions including structural failure and limited road passage. Based on the modelled surface water profiles under existing conditions, the effectiveness of mitigation to safely convey flows at the 17th St. Bridge and the 102nd Ave. crossing are most easily compared between the Upgrade options, and between the Storage and Combination options, separately. The effectiveness is described in terms of the binary results of overtopping or no overtopping (i.e., safe flow conveyance), and backwatering or no backwatering.

For the Upgrade options, the mitigation effectiveness of the Upgrade-1 and Upgrade-2 options is the same. The effectiveness of the mitigation, compared to existing conditions, can be summarized as follows:

- Floods of higher magnitude than the 2% AEP (i.e., the 1% and 0.5% AEP floods) result in overtopping and backwatering at both crossings with and without mitigation. Therefore, the proposed mitigation has limited benefit at these flows.
- Floods of lower magnitude than the 20% AEP (i.e., the 50% AEP flood) are safely conveyed with mitigation, but this also occurs under existing conditions. Therefore, the proposed mitigation has limited benefit.
- Mitigation creates safe flow conveyance, compared to existing conditions, for magnitudes ranging from the moderately low to the moderately high (10% and 2% AEP) floods, respectively, as follows:
  - For the moderately low (10% AEP) flood, overtopping and backwatering are avoided at the 17th St. Bridge. At the 102nd Ave. crossing, overtopping already does not occur under existing conditions, but backwatering is reduced due to the mitigation.
  - For the moderately high (2% AEP) flood, the flood benefits at the 17th St. Bridge are limited (overtopping and backwatering occur). However, due to the mitigation, overtopping and backwatering are avoided at 102nd Ave.

For the Storage and Combination options, the results are only compared for the 0.5% AEP flood, which was used to define the appropriate storage volume. The mitigation effectiveness, compared to existing conditions for the 0.5% AEP flood, can be summarized as follows:

- Mitigation is effective at safely conveying flows through the 102nd Ave. crossing; however, backwatering occurs.
- Mitigation improves conditions at 17th St.; however, overtopping and backwatering still occur.

Floods of lower magnitude than the 0.5% (i.e., the 1%, 2%, 10%, 20%, and 50% AEP floods) would show progressive improvements for safe flow conveyance at 17th St. and 102nd Ave. crossings; however, the details of overtopping and backwatering for those AEP floods were not specifically assessed in this study.

9.1.5 Key Findings and Considerations

The following summarize key findings from the hydraulic analysis to be carried forward to the discussion on a preferred approach:

- Recent and planned upgrades implemented since the 2016 flood event have likely resulted in flood hazard reductions in the area of the 17th St. Bridge and downstream.
- Increasing flow capacity to reduce flooding at 102nd Ave. can be reasonably achieved. However, the Upgrade options will not safely convey flood magnitude events that are higher than the moderately high magnitude flood (2% AEP).
- The flood benefits of the Upgrade options are localized to 102nd Ave. and the 17th St. Bridge.
- Based on comparisons of the very high flood (0.5% AEP), the Storage and Combination options are more effective at reducing flood depths at the points of interest. This is especially true for locations upstream from the 17th St. Bridge.

- With the Storage and Combination options, a modestly-sized upstream storage reservoir (9,000 m^3) could attenuate a very high magnitude flood (0.5% AEP) such that it is safely conveyed through the 102nd Ave. crossing.

If flow capacity is to be increased by upgrading the 102nd Ave. crossing:

- The Upgrade-2 option (12-m span) would reduce flood extents and backwatering at the 102nd Ave. crossing by the greatest amount.
- The potential effects associated with Upgrade-2 versus Upgrade-1 related to debris were not considered. Upgrade-2 would allow debris to pass more freely at the 102nd Ave. crossing.
- The difference in flood extent and water surface elevation reductions between Upgrade-1 and Upgrade-2 are relatively small. However, a larger span would provide other benefits (see Section 9.2).

If storage is to be constructed upstream to attenuate peak flows:

- The Combination option has the similar flood benefits as those mentioned for the Upgrade and Storage options described above.
- The Combination option demonstrates that upstream storage can be complementary to upgrading the 102nd Ave. crossing.

The next section discusses the fluvial geomorphology analysis. Then Section 9.3 builds on the previous and following analyses to discuss the preferred approach.

9.2 Fluvial Geomorphology Analysis

Fluvial geomorphological form and processes must be considered when designing crossing structures to minimize the risk of damage from river migration and bed scour, and to avoid the need for future channel realignment or unnecessary hardening. Likewise, the crossing should not disturb natural fluvial geomorphological processes, which could impact channel hydraulics and local aquatic and riparian habitats. Comments on the mitigation options are provided in the following sections based on the hydraulic model output for the lower magnitude and more frequent flood events, since these events have the greatest effects on geomorphological processes.

9.2.1 Historical Changes

The 102nd Ave. crossing is located within Reach 2, as defined in the Fluvial Geomorphology Assessment (Appendix E – Palmer). Reach 2 was extensively realigned/straightened between 1959 and 1984 (refer to the Fluvial Geomorphology map book, attached to Appendix E). More specifically, Reach 2 was straightened between 17th St. and 102nd Ave. between 1959 and 1970 (Figure 45), resulting in approximately 26% loss of total channel length between these two road crossings. The planform between the two crossings has remained consistent since 1970. The existing crossing can be observed in the 1970 aerial photos but not in the 1959 aerial photos (the previous crossing type and dimensions are unknown).

Based on field observations, numerous erosion protection strategies have been attempted immediately downstream of 102nd Ave. where concentration of flow has exacerbated bed and bank/slope erosion.

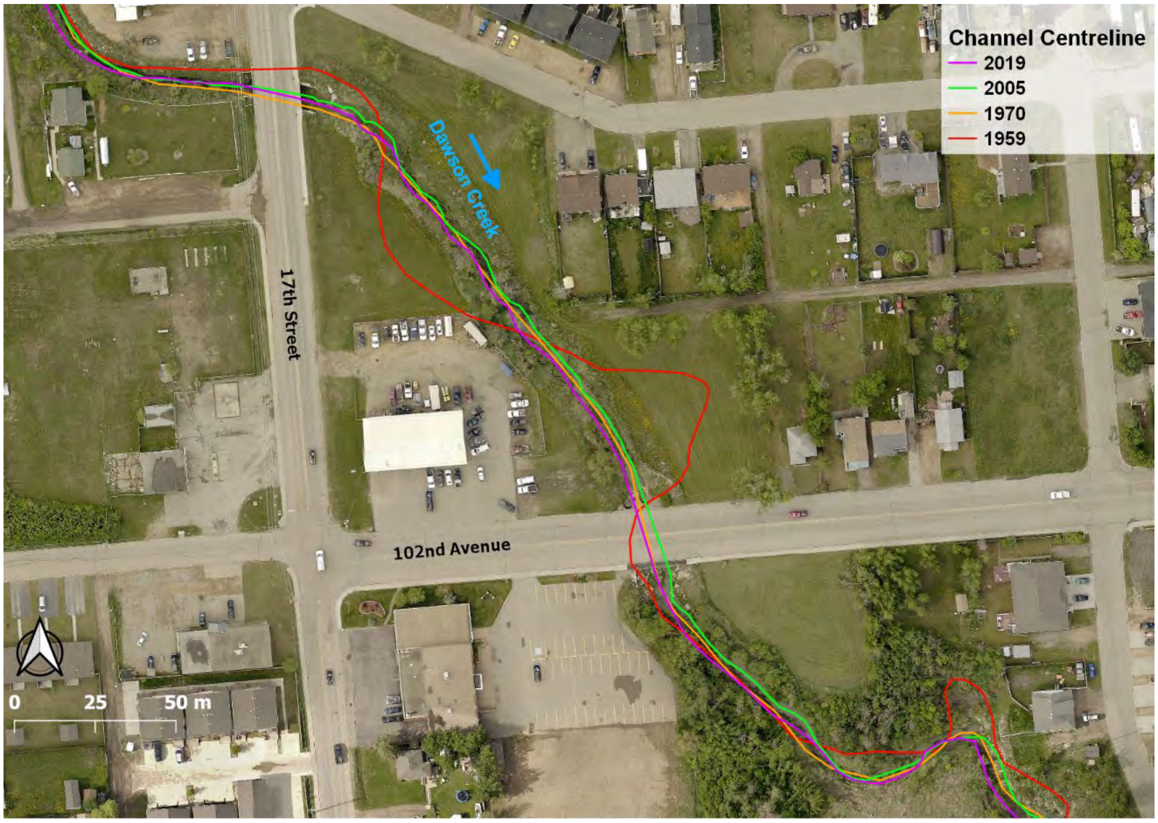

Figure 45: Historical planform of Dawson Creek near 102nd Ave.

9.2.2 Existing Conditions

The two corrugated steel pipe (CSP) culverts at 102nd Ave. are a longitudinal grade control. The culverts locally decrease the energy gradient upstream, leading to sediment deposition. The culverts concentrate flow and locally increase the energy gradient downstream, leading to excess bed and bank scour. As well, the combined width of the two CSP culverts (5 m) is less than the bankfull width of Dawson Creek (approximately 8 m) near 102nd Ave., which laterally constricts the channel through the crossing. As such, the existing crossing does not accommodate lateral or vertical adjustments of the channel boundary.

Upstream of 102nd Ave., both banks are locally collapsing (Figure 46). The lack of riparian vegetation has reduced bank strength. The alternating pattern of erosion along both banks may be a precursor to re-adoption of a sinuous planform, which is common for human-caused straightened channels. As well, bed aggradation (raising of the channel bed as a result of sediment deposition) upstream of 102nd Ave. has prevented water from accessing the west culvert during low-flow conditions and is likely increasing upstream flood elevations. Downstream of 102nd Ave., bed and bank erosion has been exacerbated by concentration of flow through the undersized culverts. Haphazard bank protection has failed; some of the material placed along the bank to mitigate erosion has been transported and deposited approximately 15 m downstream of the crossing. Ongoing fluvial erosion has contributed to slope instability along both sides of the channel downstream of the crossing. Retrogressive slope failures along the west bank have reduced the area of the parking lot at Bergeron Funeral Services and Crematorium over the period of photographic record. As well, tension cracks were observed in the parking lot near the top of slope during field reconnaissance in August 2019.

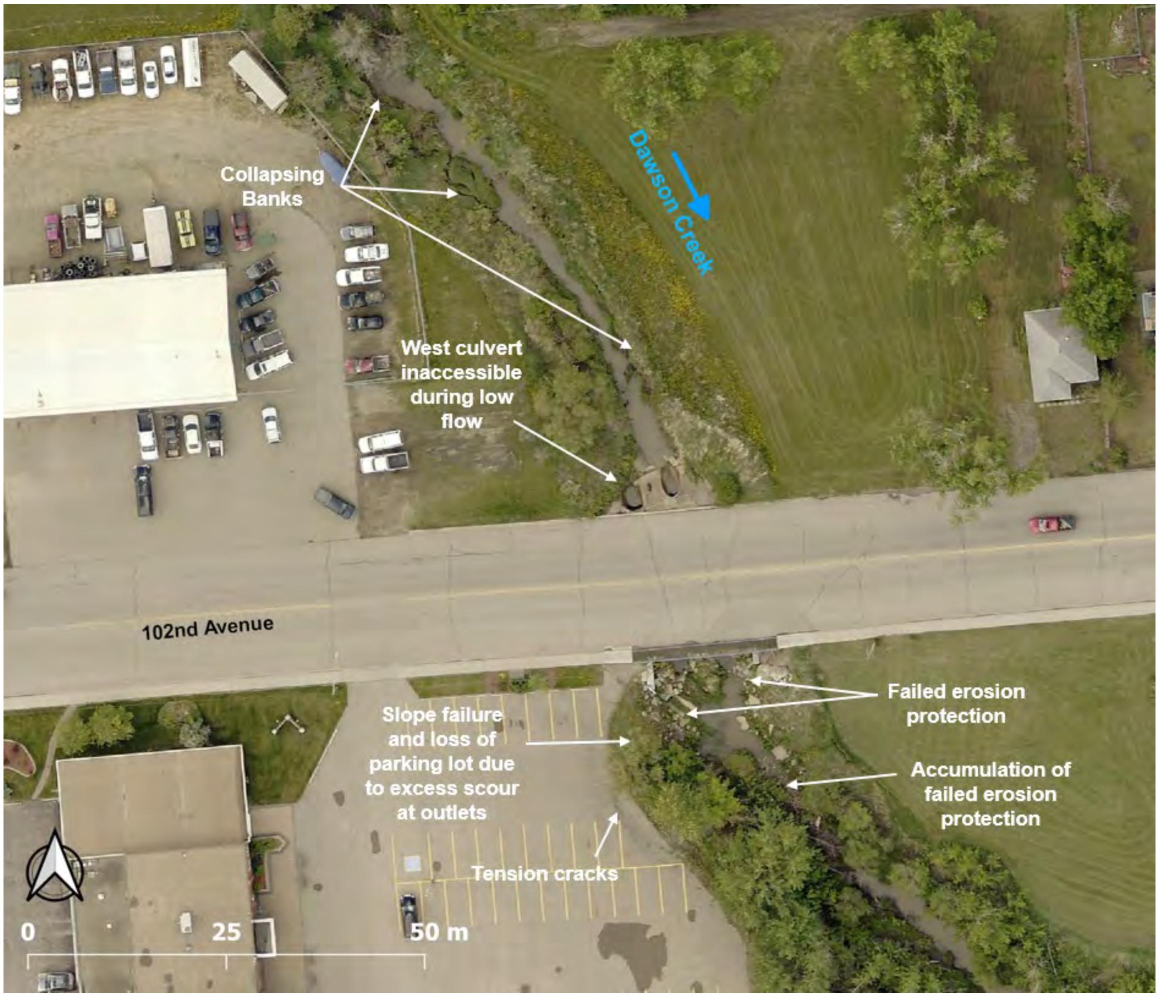

Figure 46: Existing geomorphological issues and considerations near the 102nd Ave. crossing of Dawson Creek.

9.2.3 Upgrade Option Commentary

The proposed options for increased flow capacity (Upgrade, and Combination) would improve geomorphological conditions and erosional issues near 102nd Ave. A 3 m-high culvert should be sufficient to accommodate the free passage of rafted large woody debris and/or ice during the low and moderately low (20% AEP and 10% AEP) flood magnitude events. As well, a larger flow area through the crossing would reduce backwatering during high flood events (Figure 41), which would reduce excess sedimentation (upstream) and erosion (downstream) near the 102nd Ave. crossing. Similarly, both Upgrade options would increase velocity upstream (Table 29) of 102nd Ave. and decrease velocity downstream of 102nd Ave., which would reduce excess sedimentation (upstream) and erosion (downstream).

An 8-m span (Upgrade-1 option) is approximately the bankfull width of the watercourse. This span can accommodate sediment conveyance under existing conditions but there is no allowance for natural lateral adjustments (e.g., bank erosion). In comparison to existing conditions, the velocity for the low flood event (20% AEP) will increase notably upstream of the crossing for an 8-m span culvert (Table 29), which will reduce sedimentation and could cause the channel to incise through the sediments that have accumulated over the past 50 years. Velocities downstream of the crossing will decrease, which will reduce bank and bed erosion potential. The observed upstream bank erosion suggests the previously straightened watercourse may be regaining sinuosity. A slight increase in sinuosity would not be properly accommodated by an 8 m span. Furthermore, the discharge of high frequency flood events (50% AEP, 20% AEP) along Dawson Creek is projected to increase over the coming decades as a result of climate change (Table 11). Larger discharges can widen the watercourse. Dawson Creek may therefore become wider in the vicinity of the 102nd Ave., over the coming decades, so an 8-m span may no longer accommodate the bankfull channel width.

A 12-m span (Upgrade-2 option) is greater than the bankfull channel width. This span can accommodate natural sediment conveyance as well as some lateral adjustments (e.g., bank erosion and increased sinuosity). In comparison to existing conditions, the velocity during the low flood event (20% AEP) will increase notably upstream of the crossing for a 12-m span structure (Table 29), which would reduce sedimentation and could cause the channel to incise through the sediments that have accumulated over the past 50 years. Velocities downstream of the crossing will decrease significantly (more than for Upgrade-1), which will reduce bank and bed erosion potential. As well, a 12-m span can accommodate channel widening that may result from higher flow events in the coming decades. Accommodation of these lateral adjustments and a wider channel would reduce the risk of excess sedimentation and erosion near the crossing.

Table 29: Comparison of change in velocity near 102nd Ave., for the Upgrade options, for the 20% AEP.

20% AEP	Velocity (m/s)				
Location Relative to 102nd Ave.	Existing Condition	Upgrade-1	Upgrade-1 Change	Upgrade-2	Upgrade-2 Change
63 m upstream of inlet[1]	0.86	1.39	0.53	1.47	0.61
17 m upstream of inlet[1]	0.69	1.17	0.48	1.40	0.71
Inlet	1.42	1.47	0.05	1.37	-0.05
Outlet	1.47	1.25	-0.22	1.05	-0.42
11 m downstream of outlet[1]	1.42	1.27	-0.15	1.29	-0.13
50 m downstream of outlet	1.10	1.09	-0.01	1.10	0.00

Note 1: Locations of existing bank/bed erosion.

9.2.4 Storage and Combination Options Commentary

If no changes are made to the existing crossing structure at 102nd Ave., the erosional issues associated with the existing crossing would persist. As such, upstream storage to reduce peak discharge and flood elevations at 102nd Ave. during high flow will not improve the geomorphological function of the Dawson Creek at 102nd Ave. To store enough volume of water to adequately alter the hydrograph for flood reduction benefits, a 9,000 m^3 reservoir would need to be constructed. Tradeoffs associated with this reservoir land use should be considered.

9.2.5 Key Findings and Considerations

The following summarize the key findings from the fluvial geomorphological analysis to be carried forward to the discussion on a preferred approach:

- Changes to the existing 102nd Ave. crossing are necessary to address erosional issues.
- Maximizing the flow capacity at the 102nd Ave. crossing (i.e., Upgrade-2, 12-m span) would decrease velocities significantly at the crossing, which would reduce bank and bed erosion potential (more so than Uprade-1, 8-m span).
- A 12-m span crossing upgrade at 102nd Ave. could accommodate channel widening that may result from higher flow events in the coming decades. This is important considering the effects of climate change.
- Upstream storage to reduce peak discharge and flood elevations at the 102nd Ave. crossing during high magnitude floods would not improve the geomorphological function of the Dawson Creek in the area of the 102nd Ave crossing.
- Upstream storage presents an opportunity to improve geomorphological function in the upstream areas of Dawson Creek.

If flow capacity is to be increased by upgrading the 102nd Ave. crossing:

- Clear-span bridges (i.e., most similar to the Upgrade-2 option, 12-m span) are most often recommended to increase flow capacity.
- If considering a culvert (i.e., most similar to the Upgrade-1 option, 8-m span) an "open-bottom" is highly recommended. These types of culverts allow for vertical bed adjustments and accommodate natural sediment transport processes. Closed-bottom culverts do not allow the bed to vertically adjust. As well, closed-bottom culverts act as a grade control, which can lead to excess sedimentation and erosion near the culvert inlet and outlet (similar to existing conditions at 102nd Ave.).
- Regardless of the flow capacity increase that is chosen to mitigate flood and erosion risk in the 102nd Ave. area, the banks immediately upstream and downstream of the crossings should be regraded to a slope gentler than 2H:1V and stabilized using bioengineering measures such as a vegetated boulder revetment. Care should be taken to ensure smooth upstream and downstream transitions with the existing banks, as unnatural irregularities could induce or exacerbate erosion.

If storage is to be constructed upstream to attenuate peak flows:

- The City may want to reconsider the use any land that is available to construct a reservoir. Instead, that land could be used to increase channel length through the construction of a sinuous channel

along a sub-reach that has been historically straightened. Replacing a straightened sub-reach with a meandering channel would improve the geomorphological function of the Dawson Creek, increase aquatic and riparian habitat, and improve flood storage.
- If a reservoir is constructed, it should be strategically located and protected by suitable erosion protection to ensure the adjacent channel cannot avulse into the off-line reservoir.

9.3 Preferred Approach

Overall, this analysis shows that flooding cannot be feasibly mitigated in all areas of the City, and for all flood events. Furthermore, structural mitigation causes fluvial geomorphological effects upstream and downstream. The evaluation has also demonstrated that the 3 mitigation options considered are not mutually exclusive. Rather they can be complementary to achieve flood reduction in the Dawson Creek. The City needs to prioritize the flood benefits that are desired. While the analyses in the previous sections can facilitate prioritization, important gaps remain to better understand feasibility issues such as costs, regulations, and timelines.

Based on the conceptual evaluation completed, if a single option is be prioritized to reduce flooding at 102nd Ave., the Upgrade-2 option (12-m span) is recommended. This option will provide flood benefits that include:

- Allow safe crossing during flood events and reduce backwatering (up to a moderately high flood).
- Reduce damage in the area to protect homes and businesses.
- Reduce sedimentation upstream and erosion downstream from the crossing.
- Reduce the potential for debris to create blockages at the crossing.
- Allow for channel migration without affecting the new structure, making it more resilient to climate change.

However, recognizing that the benefits of the above upgrade project would be relatively localized to the 102nd Ave. area, it is recommended that this mitigation option be implemented with a long-term view to considering complementary upstream storage options. The upstream storage could be planned and constructed on a timeline that is independent of the upgrade project. Furthermore, increasing upstream storage by reintroducing meandering river channel length should be considered alongside a purpose-built reservoir. An off-stream channel can potentially bring many co-benefits to the community of Dawson Creek including environmental, recreational, and economic.

Considering a combination of options is likely the best way to alleviate flood issues in Dawson Creek over the long term. This approach can provide the City with flexibility as it manages flood while considering the dynamic and interconnected Creek system, and the uncertainties associated with climate change.

These structural options represent only one type of potential mitigation. Non-structural options, such as land use changes and building regulations, are generally more effective at reducing flood damages and risk. They must also be considered in the development of a larger flood strategy.

10 Next Steps

Based on the tasks and deliverables from this project, the City has a greatly improved understanding of flood hazard and important erosion hazards. The mapping products can now be used for a range of purposes including defining land use and building policy. Specific recommendations are provided in the following sections. These are preceded by a review of the flood risk planning process.

10.1 Progress on Flood Risk Reduction Planning Process

A process for flood risk reduction and increased resilience, based on best practice for flood management, was presented in the FMPR and summarized in Section 3. Table 30 outlines how this flood mapping project has progressed the City through the flood risk reduction process.

Table 30: Progress of risk reduction process steps based on previous report and this report.

Step		Progress	
		FMPR	This Report
1.	Acknowledge problem and set the stage	100%	100%
2.	Identify and establish hazards	50%	100%
3.	Identify exposure and vulnerability	95%	95%
4.	Identify consequence and risk	95%	95%
5.	Establish objectives and measures of success	50%	50%
6.	Identify flood mitigation options	50%	80%
7.	Identify preferred options	5%	50%
8.	Develop Adaptive Implementation Plan	0%	0%

With the completion of this flood mapping project, the City has completed Steps 1 and 2 of the flood risk reduction process. Significant gains have also been made in steps 2 to 7, and flood mapping will now allow those steps to be advanced in the next phase of work. When these steps are completed, it will be time to develop an adaptive implementation plan (step 8). Future steps that the City takes toward flood mitigation should be completed within the context of reducing risk through the above planning process.

10.2 Recommendations

Building on the deliverables of this project, the following are recommended actions. In some cases, the recommendations entail working with, or supporting, external partners.

- **Use information from the flood mapping products to inform and update land use policies.** It is essential that flood hazard maps and FCLs are reflected in applicable land use policies and regulations, such as Official Community Plans (OCPs), development permit areas (DPAs), and updates of the floodplain bylaw. In the short-term, the 0.5% AEP flood extent map (with freeboard) should be incorporated into City policy; however, in the longer-term, working iteratively with the OCP process, consideration of multiple AEP floods, flood hazard severity and climate scenarios should be included in policy. This will effectively allow for different land uses and building types where hazards have different characteristics (e.g. likelihood, depth and velocity). Further, the erosion hazard mapping should be used in tandem to inform land-use policy (see next bullet).

- **Integrate secondary hazards associated with fluvial geomorphological processes into flood planning processes.** As the City considers upgrades to undersized culvert crossings, it should complete landsliding hazard assessments/mapping, and determine depths of cover above buried infrastructure. The City should limit future channel realignment and riparian vegetation removal, and it may wish to update zoning and planning tools based on documented flood, erosion, and landslide hazards. For instance, the *Freedom Space for Rivers* concept (Biron *et al.*, 2014) incorporates flood hazards, erosion hazards, landslide hazards, and riparian wetlands to establish development limits that account for extreme events associated with climate change and land use change. Site-specific mitigation or even expropriation may be required where existing development is within the limits of the established hazards.
- **Make the flood and fluvial geomorphological erosion mapping products public.** Research shows that it is in the City's best interest to disclose the flood hazard mapping products from this project publicly. It is essential that the general public has access to information on where it may flood in the future. To assist in this, an overview designed for communications with the public is also available. The overview outlines the purpose, approach, results, and limitations of this project and can be used as a companion document to the Flood Hazard Map Atlas to start a community conversation on actively preparing for flood under a range of events that are expected now and in the future under climate change. Digital data files for flood depths, flood extents and FCL reaches were provided to the City of Dawson Creek along with this report. We recommend adding these GIS files to the City's Online GIS/Mapping system, along with the provided metadata. This will allow future studies to use this information, and by doing so, increase the general knowledge of flood hazards in Dawson Creek.
- **Consider a mix of structural and non-structural mitigation options.** A limited number of structural mitigation options were evaluated to reduce flooding at the 102nd Ave. crossing. The evaluation highlighted that different options provide different flood benefits, which are not mutually exclusive. This type of analysis should be conducted in all of the City's flood mitigation activities. Furthermore, analyses should be expanded to consider non-structural mitigation options as complementary tools to reduce flood damages. Carefully considering a range of options is likely to provide the City with flexibility in future flood mitigation activities. This will help the City become resilient in facing the uncertainties from climate change. Once a wider set of preferred options are identified, the City should endeavour to better understand feasibility issues such as costs, regulations, and timelines.
- **Work with regional partners to improve flood hazard management regionally**. Flows into Dawson Creek originate outside of its municipal boundaries, and flood management is best considered at a watershed scale. Local government (Peace River Regional District), provincial agencies (BC Hydro, BC Ministry of Transportation), the oil and gas industry (BC Oil and Gas Commission), and the insurance industry all have interests in the area and there is opportunity to share data and water management information. These organizations would benefit from the flood mapping products resulting from this project.

- **Work with local insurance agents to support residents in understanding their flood policies.** The mapping products can complement insurance-based information to help property owners make decisions about protecting their properties. Federal policies such as the Disaster Financial Assistance (DFA) program are shifting rapidly; one clear recent direction is the expectation that disaster funds will not be available in areas where overland flood insurance can be purchased. Residential flood insurance is now available in Dawson Creek, and therefore DFA may not be granted. The City should work with the Insurance Bureau of Canada, and its local agents, to provide information to residents about changes such as these.
- **Continue to collect hydrometric data.** The City's initiative to establish a local monitoring program over the last year is laudable. These data will become more valuable over time, helping the City better understand flood and related hazards. Section 5.3.2 contains specific recommendations to improve the City's monitoring program. Similarly, agencies operating hydrometric stations in the region, such as the Water Survey of Canada, need to continue operating—and expanding their existing—networks. The region is currently hydrologically data-scarce, as agencies such as the WSC are understaffed. The need for more data at local and regional scales is becoming increasingly important. As the influences of climate change increase, the ability to rely on past datasets to predict future hydrologic conditions decreases.
- **Integrate the hydraulic model into stormwater management planning.** When appropriate, the *Drainage Master Plan* should incorporate the riverine hydraulic model to assess and mitigate backflow hazard. The PCSWMM boundaries at the downstream end of the network should be updated based on the output from the hydraulic model (i.e., if the design storm is being run in the stormwater drainage model, downstream boundaries should be set to the 20% AEP event, as this event most closely matches the design storm). Priority outfalls and their networks should be identified to be maintained and replaced if necessary. Flood impacts to the stormwater drainage system should be revisited based on new infrastructure projects that could affect creek channel dynamics.

11 Conclusions

As the City of Dawson Creek works towards becoming more resilient to flooding, an essential first step is the update of flood hazard maps. The mapping deliverables from this project now empower the City to better understand—and plan—around flood and related hazards.

The analyses showed that the 2016 event was a moderately high to high magnitude flood (1.3% AEP). Under climate change, floods like the 2016 event are projected to become larger. However, it is projected that changes are likely to be larger for the lower magnitude floods (i.e., low and very low magnitude floods are likely to occur more frequently in the future). Climate change is also likely to exacerbate the fluvial geomorphological changes, and stormwater drainage issues highlighted in the supporting assessments.

The structural mitigation that has been implemented since 2016 has already made a difference in reducing flooding. This supports the City's desire to reduce flooding at the 102nd Ave. crossing through further structural mitigation projects. While results from the limited set of options evaluated suggest that this is achievable, it is clear that flooding cannot be mitigated structurally at all locations and for all magnitude floods. A greater set of tools, including non-structural mitigation, is required to reduce overall flood risk.

We hope this work can be a base for the continuing efforts of the City of Dawson Creek to support key initial decisions regarding flood mitigation and capital cost allocations. The City can now make more informed decisions to make the community more resilient to floods and other hazards and prepare for the impacts of a changing climate.

12 Glossary

Term	Definition	Source
Annual Exceedance Probability (AEP)	The probability of an event of a given magnitude occurring in any given year, expressed as a percentage.	
(Asset) Encounter Probability	The probability that an asset will be affected by a hazard of a given magnitude in a given time period.	
Avulsion	A rapid change in the course or position of a river channel by incision (erosion), commonly in association with meander a cut-off that shortens channel length, reduces sinuosity and increases gradient.	
Chute channel	A secondary channel that is formed across the floodplain during the inundation of a meander bend (i.e. flood), which may eventually lead to a channel cut-off.	
Confinement	The constraint on the lateral movement of a watercourse by valley walls, a resistant geologic outcrop, or an anthropogenic formation.	
(Landslide) Encounter Probability	The probability that any given area will be affected by a landslide over a given time period.	
Flood	Overflowing of water onto land that is normally dry. It may be caused by overtopping or breach of banks or defences, inadequate or slow drainage of rainfall, underlying groundwater levels, or blocked drains and sewers. It presents a risk only when people and human assets are present in the area where it floods.	RIBA
Frequency	The number of occurrences of an event in a defined period of time.	PSC
Glaciolacustrine	Sediment deposited along the bed of glacial lake.	
Hazard	A potentially damaging physical event, phenomenon, or human activity that may cause the loss of life, injury, property damage, social and economic disruption, or environmental degradation. Hazards can include latent conditions that may represent future threats, and can have different origins: natural (geological, hydrometeorological, and biological) or be induced by human processes. Hazards can be single, sequential, or combined in their origin and effects. Each hazard is characterized by its location, intensity, frequency, and probability.	UNISDR
Hazard Assessment	Acquiring knowledge of the nature, extent, intensity, frequency, and probability of a hazard occurring.	MODIFIED NDMP TO MATCH HAZARD

Term	Definition	Source
(Natural) Hazard	Natural process or phenomenon that may cause loss of life, injury, other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.	UNISDR
Large woody debris	Logs, sticks, and other wood within the active channel that influence flow patterns.	
Longitudinal Profile	A visual representation of the channel slope derived from topographic data.	
Likelihood	A general concept relating to the chance of an event occurring. Likelihood is generally expressed as a probability or a frequency of a hazard of a given magnitude or severity occurring or being exceeded in any given year. It is based on the average frequency estimated, measured, or extrapolated from records over a large number of years, and is usually expressed as the chance of a particular hazard magnitude being exceeded in any one year.	RIBA
Meander migration	Evolution of a meander through time caused by erosion along the outside of a meander bend and deposition along the inside of a meander bend.	
Meander planform	A channel geometry, identified in plan view, that exhibits regular, sinuous curves that have similar wavelengths, amplitudes and radii of curvature.	
Mitigation	This report was written primarily with a disaster risk reduction lens and has adopted standard terminology from this field. Mitigation, in this case, relates to strategies or measures that are used to directly reduce natural hazard impacts or risk. In climate adaptation literature, mitigation often refers to local or global efforts to reduce greenhouse gas emissions.	
Oxbow	A horseshoe-shaped abandoned meander loop on a floodplain or alluvial terrace caused by an avulsion or cut-off.	
Probability	In statistics, a measure of the chance of an event or an incident happening. This is directly related to likelihood.	PSC
Pool-riffle bed morphology	Sections of channel that have an undulating bed that defines a sequence of bars, pools (i.e. deep, low gradient), and riffles (i.e. shallow, high gradient).	
Reach	Lengths of channel that display similar physical characteristics and have a setting that remains nearly constant along their length.	
Resilience	The ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.	UNISDR
Risk	The combination of the probability of an event and its negative consequences.	UNISDR

Term	Definition	Source
Risk Assessment	A methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods, and the environment on which they depend. Risk assessments (and associated risk mapping) include: a review of the technical characteristics of hazards, such as their location, intensity, frequency, and probability; the analysis of exposure and vulnerability, including the physical, social, health, economic, and environmental dimensions; and the evaluation of the effectiveness of prevailing and alternative coping capacities, with respect to likely risk scenarios. This series of activities is sometimes known as a risk analysis process.	UNISDR
Sediment transport	Downstream transport of sediments as a result of flowing water.	
Sinuosity	The ratio of channel length to valley length.	
Shear stress	In the context of fluvial geomorphology, the force per unit area parallel to the channel boundary (i.e. bed and banks).	
Suspended sediment	Fine sediment transported in suspension within the water column.	
Terrace	Flat-topped or stepped landform that represents a history of past fluvial or meltwater deposition followed by incision or downcutting.	
Thalweg	A longitudinal flow path along the deepest point of the river.	
Turbidity	The haziness or cloudiness of a fluid caused by floating particles in water, generally visible to the naked eye.	
Unconfined	A watercourse that is able to migrate freely within its floodplain in any direction.	

13 References

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Appendix A Topographic Surface Development (Vector)

This appendix is provided as a separate digital file.

Appendix B Hydrology and Climate Change Background

This appendix is provided as a separate digital file.

Appendix C Hydraulic Model Documentation

This appendix is provided as a separate digital file.

Appendix D Flood Hazard Map Atlas

This appendix is provided as a separate digital file.

Appendix E Fluvial Geomorphology Assessment (Palmer)

This appendix is provided as a separate digital file and included with printed hard copies of the report.

Appendix F Stormwater Drainage Assessment and Channel Conditions Survey

This appendix is provided as a separate digital file and included with printed hard copies of the report.

Appendix G Flood Mapping Assurance Statement

This appendix is provided with printed hard copies of the report.