Flood Mapping for Small Creeks on the Canadian Prairies: Challenges and Strategies - Stettler Flood Mapping Case Study

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ABSTRACT

Effective flood risk management and land-use planning depend on accurate, realistic flood mapping. In a country as large and diverse as Canada, flood mapping must account for varied landscapes, multiple flood mechanisms, different land uses, and a broad range of waterbody types. These factors create unique challenges that demand site-specific methodologies. This paper examines two challenges encountered in flood mapping along small prairie creeks: estimating flood frequency flows for ungauged small streams and delineating inundation maps at road crossings with limited culvert capacity. It then introduces strategies to improve flood mapping accuracy. Using the study for the town of Stettler, Alberta as a case, we demonstrate the importance of site-specific analyses, often overlooked in large-scale or regional studies.

Flood frequency analysis was challenged by limited hydrometric data available, floodplain attenuation, and lake storage effects in the basin upstream of the study site. To overcome this, we developed a site-specific, physical process-based approach that integrates local knowledge into a regional flood frequency analysis, accounting for flood flow attenuation due to upstream lake and floodplain storage. This produced more reliable flood frequency estimates than standard statistical methods and more accurate inundation and hazard maps.

In the Stettler study, accurately representing potential road overtopping and flood inundation at 27 culvert crossings was another challenge. Inundation mapping at culvert crossings typically employs a sloped water surface across road embankments. However, this approach can produce unrealistic results at a crossing where the downstream water level is well below the road crest while the upstream water is significantly higher. To address this issue, we employed GIS techniques that better represent the local hydraulic condition without more complex numerical modelling. This method accurately mapped road overtopping at several locations where the conventional mapping approach failed to identify it.

KEYWORDS: Flood Mapping, Flood Hydrology, Inundation Mapping at Culvert Crossing

1 INTRODUCTION

The Canadian Prairies, spanning Alberta, Saskatchewan, and Manitoba, feature flat to gently rolling terrain, small low-gradient streams, and wide floodplains that are highly susceptible to flooding from spring snowmelt and intense rainfall. This paper focuses on the Stettler Flood Study, which was completed in 2022-2025 by Northwest Hydraulic Consultants (NHC) for Alberta Environment and Protected Areas (EPA). Flood maps were developed for 30 km of Redwillow Creek and 4 km of an unnamed tributary flowing through the town of Stettler and surrounding areas of Stettler County in east-central Alberta.

Flood mapping is essential for rural communities like Stettler, supporting flood protection, emergency preparedness, land-use planning, and infrastructure design. Past events, most notably the 1974 flood (which affected many prairie communities in Alberta and Saskatchewan), have demonstrated the region's vulnerability. Prairie flood studies also face some site-specific challenges which are unique to this landscape. In Stettler, these included difficult surveying conditions due to poorly defined channels, intermittent flows, marshy areas, and deep-water pools created by beaver dams; complex hydrology in ungauged basins; mapping limitations at culvert crossings; and Digital Terrain Model (DTM) distortions caused by floodplain vegetation. This paper focuses on two technical challenges: developing hydrology for ungauged prairie streams and mapping roadway overtopping at culvert crossings.

2 FLOOD HYDROLOGY

Reliable flood mapping requires accurate peak flow estimation. Studies like the Stettler Flood Study require modelling and mapping multiple flood frequencies based on careful assessment of basin responses under different flood magnitudes. This section summarizes the challenges and methods used to develop flood hydrology for Redwillow Creek and the unnamed tributary in the Stettler Flood Study. Local knowledge indicated that peak flow estimates from some previous studies in the region were unrealistically high, prompting a refined, evidence-based approach for more accurate flood mapping.

2.1 Watershed Characteristics

Flood hydrology assessment in ungauged watersheds typically relies on regional flood frequency analyses because local flow measurements are not available. This approach demands accurate delineation of the basin area and its physiographic characteristics. In prairie basins, flat terrain with numerous lakes and wetlands complicate basin delineation and the determination of contributing areas. Overcoming these challenges requires local knowledge, high-resolution topographic data, and representative regional hydrologic data to refine and verify basin contributing areas, as outlined below for the Stettler Flood Study.

The Redwillow Creek basin, including the unnamed tributary, is shown in Figure 1. The basin features flat terrain with extensive wetlands and sloughs that are typical of prairie landscapes. Agriculture is the dominant land use. Redwillow Creek flows northwest through Stettler and is ungauged within the study reach. A discontinued gauge near its downstream end operated from 1962-1991. Available data show that annual peak flows usually occurred during spring snowmelt. The largest recorded flood occurred in spring 1974 (AEP, 1995). Another notable flood event occurred in July 1999 and was attributed to a local rainstorm, though no measurements were taken (Stantec, 2004).

Basin delineation for this study was completed using Water Survey of Canada (WSC) data, Agriculture and Agri-Food Canada (AAFC) watershed information, and LiDAR topography. Although published sources report a gross drainage area of 825 km² upstream of the discontinued Redwillow Creek gauge (WSC Station 05FC005), detailed hydrologic and topographic assessments showed that the Lonepine Lake subbasin (Figure 1) is a self-contained area and does not contribute flows to Redwillow Creek under typical conditions. It was estimated that spillover from the Lonepine subbasin would require approximately 120 mm of runoff. This greatly exceeds the design runoff depth of 35 mm for this region determined by Alberta Transportation (AT, 2006) from regional runoff envelop curves. Historical flow data from the nearby WSC Bigknife Creek gauge (Figure 1) indicate a runoff depth of only 30 mm in this gauged similar basin corresponding to the 1974 flood, the largest event on record. Because these values fall far below the estimated threshold required for spilling, the Lonepine Lake subbasin was excluded, resulting in a 228 km^2 reduction in the contributing area for Redwillow Creek at the discontinued gauge (05FC005). Moreover, the high-resolution LiDAR data indicate that, if the Lonepine Lake subbasin were to spill during an extreme event, overflow would run northeast, bypassing the Stettler study reach, and join Redwillow Creek at a downstream location. This analysis further confirmed the need to exclude Lonepine Lake subbasin in this study, a critical step to improving flood peak estimation and producing reliable flood mapping.

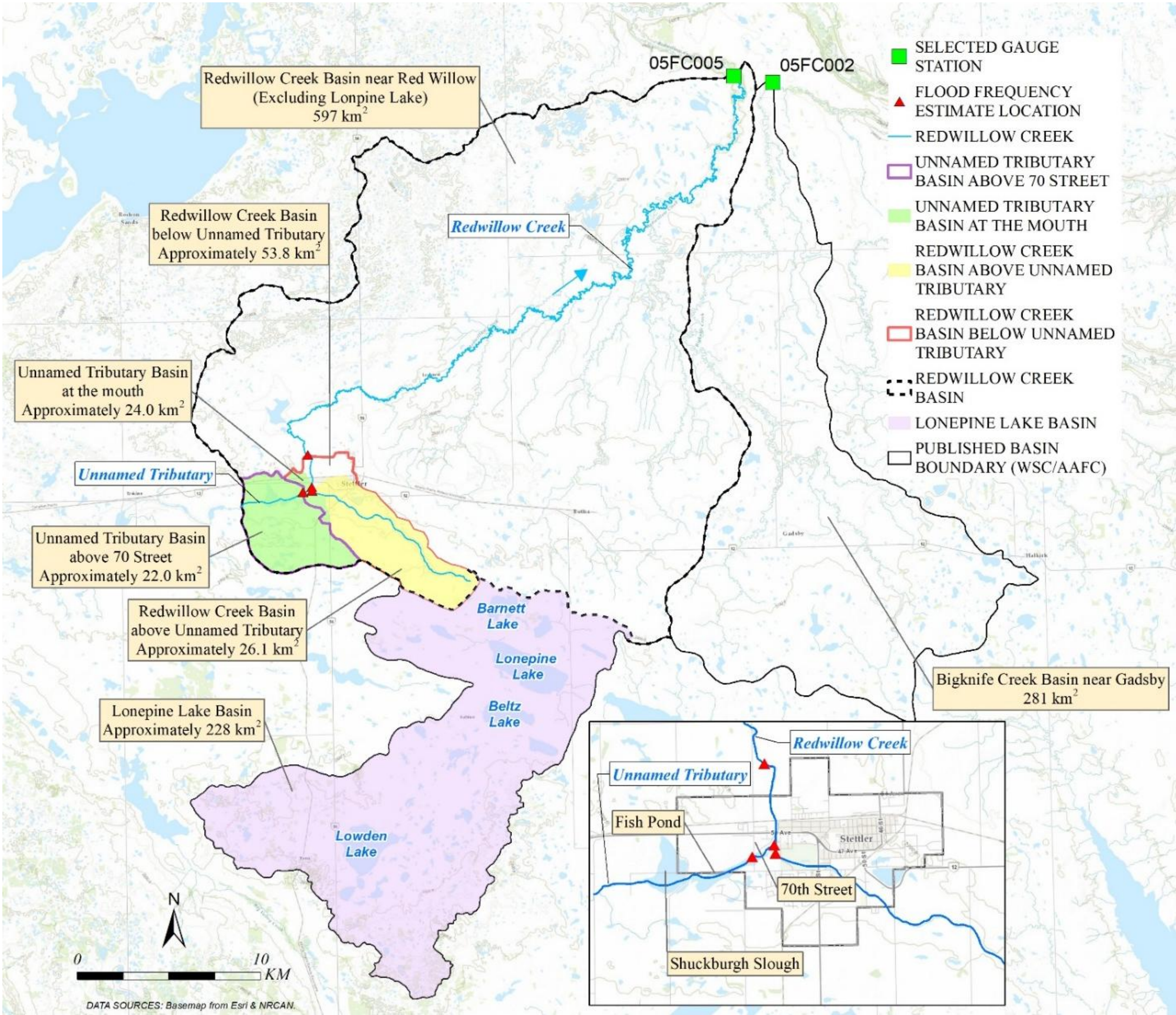

Figure 1: Redwillow Creek basin overview and selected flood frequency estimate locations

2.2 Regional Analysis

Flood frequency estimates for Redwillow Creek and the unnamed tributary were developed using a regional analysis approach, as neither stream is gauged within the study reach. Key challenges included identifying hydrologically representative basins, addressing limited gauge record lengths, and selecting a reliable relationship. Regional reference stations were chosen based on proximity, climatic and physiographic similarity, basin size, record length, and topographic characteristics. Instantaneous peak discharges from these stations were used in the analysis, with missing values estimated through correlations between instantaneous and daily peaks from overlapping years. The regional analysis produced instantaneous peak discharge estimates for multiple open water return periods (2-, 20-, 100-, 200-, and 1000-year floods presented in this paper) at two locations on Redwillow Creek and two on the unnamed tributary within the town of Stettler.

The annual peak instantaneous discharges (Q_p) for each of the selected regional stations were normalized by their mean value (Q_{pm}) and are plotted in Figure 2 (a) against their empirical return periods based on the Cunnane formula. Different theoretical probability distributions were tested for each individual station. The Pearson type III (P3) distribution generally provides the best fit for all selected stations. As such, a normalized P3 curve was used to fit the normalized regional flow data. The normalized P3 curve shown in Figure 2 (a) was computed by varying the standard deviation and coefficient of skewness within the respective ranges of the values for the selected gauge stations until the total Sum of Standard Error (SSE) values (Equation 1) for the regional stations become minimum. The SSE measures the root mean square difference between observed value (x_i) and predicted value (y_i), adjusted for the degrees of freedom $(n-m)$.

$$\mathrm{SSE} = \sqrt{\frac{1}{n-m}\sum_{i=1}^{n}(x_i - y_i)^2} \tag{1}$$

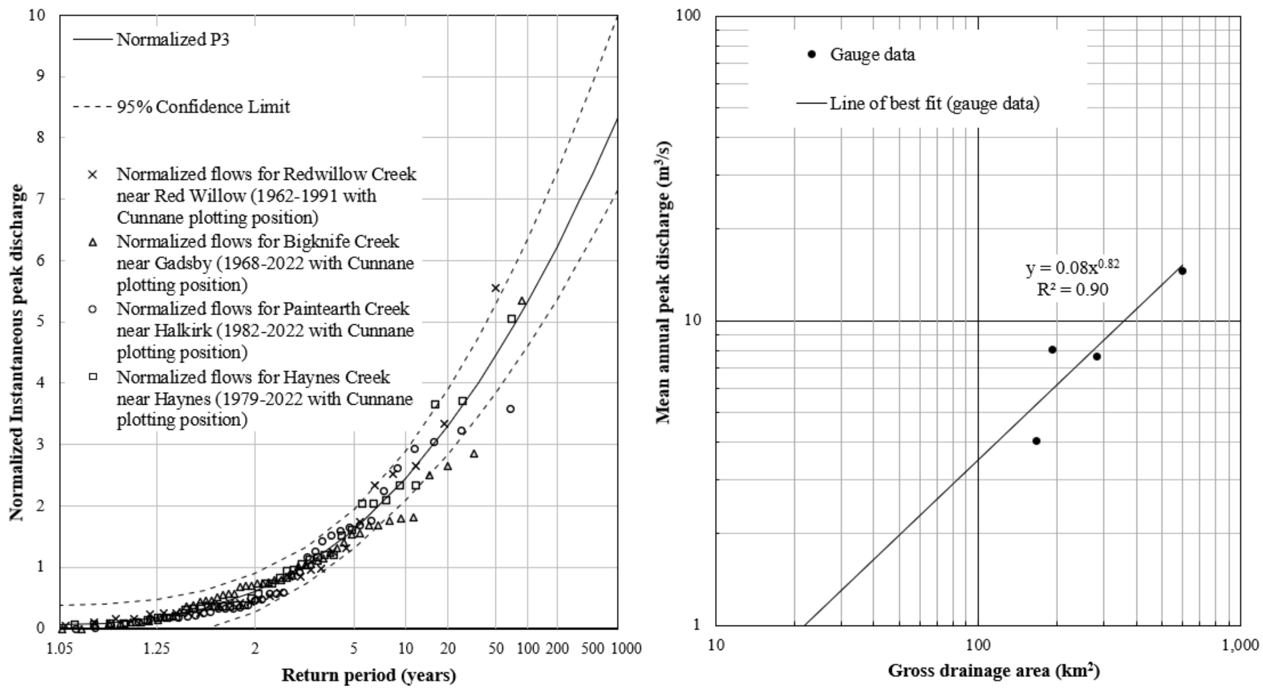

Figure 2: (a-left) Adopted P3 frequency distribution for normalized flood peak discharges and (b-right) Relationship between mean annual peak discharge and drainage area

As shown in the figure above, the curve fits all data points reasonably well. Figure 2 (a) also shows the 95% confidence limits for the normalized P3 curve, which were estimated based on the average length of the regional flood data series (41 years). Figure 2 (b) above on right side, shows the relationship between the mean annual peak discharges (Q_{pm}) and gross drainage areas for the selected regional stations. The peak discharge is proportional to the gross drainage area to the power of 0.82. Using the normalized P3 curve from Figure 2 (a) and the relationship of mean peak discharge versus drainage area from Figure 2 (b), flood frequency estimates can be developed.

To reduce uncertainty, the regional analysis used a rigorous gauge selection process and an appropriate flood frequency analysis method. A flood-index approach with normalized flows reduced bias from differing record lengths, and the best-fit curve was statistically optimized. Confidence limits were determined based on the average record length. These refinements improved the consistency and reliability of the estimates, which are summarized later in the paper.

2.3 Flood Hydrograph Routing

Steady flow modelling is typically preferred for flood mapping studies. However, it is important to assess whether channel or floodplain storage could significantly attenuate downstream flood peaks, particularly at road crossings with elevated roadways and limited culvert flow capacities that can cause significant upstream impoundment. This condition is common in small prairie streams and was encountered in the Stettler Flood Study. Within the study area, the unnamed tributary flows through a relatively large slough (known as Shuckburgh Slough) and a stormwater management facility (known as Fish Pond) before joining Redwillow Creek (Figure 1). Local observations from the 1999 flood event as documented in Stantec (2004) suggest that Redwillow Creek back flowed into this tributary and constrained tributary contributions. The LiDAR data analysis confirmed a substantial storage capacity available in Shuckburgh Slough. Within the study reach, flows move through the slough, pass through an undersized 600 mm CSP culvert at 70 Street, enter Fish Pond, and then discharge to Redwillow Creek via a 1.1 m × 1.7 m box culvert and a 750 mm CSP culvert before reaching Redwillow Creek. To account for attenuation of flood flows through this tributary, synthetic hydrographs were developed and routed through these features.

The synthetic hydrographs were developed from the gauged data for Bigknife Creek (WSC Station 05FC002). Daily flows for the five largest flood events on record, including the 1974 event, were used. These events had peak flows from 13.7 to 37.7 m^3/s with times to peak from 3 to 5 days (average 3.6 days). The recorded hydrographs were normalized by corresponding peak discharges (Q_p) and times to peak (T_p). The normalized hydrographs were then represented with a dimensionless hydrograph shape featuring a linear rising limb and an exponential recession limb (Figure 3). The recession limb follows the standard exponential decay as discussed in Chow et al. (1988) and is expressed by Equation 2.

$$Q_* = e^{(T_*-1)b} \quad (2)$$

Where Q_* is the dimensionless discharge (Q/Q_p); T_* is the dimensionless time (T/T_p); b is the recession constant, for which a value of -0.95 was adopted to fit the data. While the hydrograph shape is transferable, the time to peak scales with basin size. Based on comparisons of basin area, slope, and length, the time to peak for the unnamed tributary (basin area: 24 km^2) was estimated to be approximately 1 day, or one-third of the value for Bigknife Creek (basin area: 281 km^2). This was used along with flood peak estimates from regional analysis for Unnamed Tributary above 70 Street presented in Table 1 (discussed later) to generate synthetic flood hydrographs for the unnamed tributary (Figure 3 (b)).

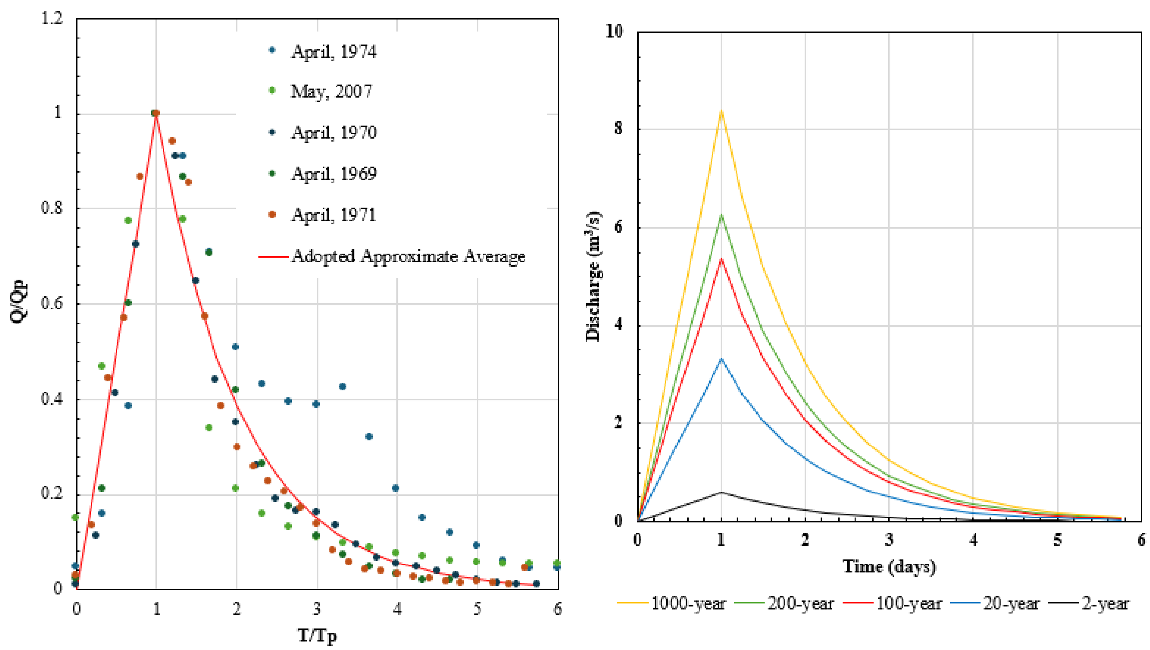

Figure 3: (a -left) Dimensionless hydrograph for the unnamed tributary (b-right) Synthetic flood hydrographs for Unnamed Tributary above 70 Street

The synthetic hydrographs for the unnamed tributary were routed through the 70 Street culvert and Fish Pond using level pool routing. The analysis indicated that the peak discharges of all flood hydrographs attenuated by 90% to 95% as flowing across 70 Street due to the limited capacity of the existing culvert and significant upstream storage. Subsequent routing through Fish Pond resulted in negligible attenuation. The routing results determined flood peak discharges from the unnamed tributary to Redwillow Creek (estimates for Unnamed Tributary at the mouth as listed in Table 1).

2.4 Adopted Flood Frequency Estimates

Table 1 presents the final adopted flood frequency estimates. Regional estimates were applied directly at Redwillow Creek above the Unnamed Tributary and at the Unnamed Tributary above 70 Street. However, because the flows in Unnamed Tributary attenuated significantly above 70 Street, adjustments were required for Redwillow Creek below Unnamed Tributary and for Unnamed Tributary at the mouth.

Table 1 Flood frequency estimates

Return period	Peak instantaneous discharge (m^3/s)							
	Redwillow Creek above Unnamed Tributary		Redwillow Creek below Unnamed Tributary		Unnamed Tributary above 70 Street		Unnamed Tributary at the mouth	
	Adopted	Without Routing	Adopted	Without Routing	Adopted	Without Routing	Adopted	Without Routing
1000-yr	9.7	9.7	11.8	17.5	8.4	8.4	1.6	9.0
200-yr	7.2	7.2	8.9	13.1	6.3	6.3	1.2	6.7
100-yr	6.2	6.2	7.6	11.2	5.4	5.4	1.1	5.8
20-yr	3.8	3.8	4.8	6.9	3.3	3.3	0.7	3.6
2-yr	0.7	0.7	0.9	1.3	0.6	0.6	0.2	0.7

For Redwillow Creek downstream of the unnamed tributary, peak flows were estimated using regional frequency curves for the reduced drainage area (excluding Unnamed Tributary above 70 Street) and then combined with the routed flows for the unnamed tributary. At the mouth of the unnamed tributary, flood peaks were determined by adding the routed outflows from the 70 Street culvert to locally generated runoff between 70 Street and the creek mouth, based on regional analysis.

Table 1 also lists flood frequency estimates based solely on the regional relationship without adjustments for routing effects. Compared with the results based on routing analysis, these estimates are noticeably higher and inconsistent with local observations at two locations. This comparison demonstrates the importance of considering site-specific conditions to develop reliable flood estimates for flood mapping.

3 MAPPING ROAD OVERTOPPING

Mapping road overtopping for various flood events is important for assessing impacts on transportation infrastructure and supporting emergency planning. Prairie creeks commonly cross small bridges and culverts that are not designed to convey 50-year or larger floods, which can complicate inundation mapping using standard 1D hydraulic modelling. The Stettler study illustrates this issue, with 27 culvert crossings along a 34 km reach, many with limited hydraulic capacity. A 1D steady-state hydraulic model was used to compute flood levels and culvert hydraulics, with the results used to inundation mapping.

3.1 Culvert Hydraulics

Culvert hydraulics directly affect upstream water levels, roadway overtopping, and local inundation. Mapping is straightforward when culvert is not overtopped or where the roadway is fully submerged; but it becomes challenging when there is a large difference between upstream headwater (HW) and downstream tailwater (TW) levels at a surcharged culvert crossing. Figure 4, adapted from WSDOT (2025), illustrates these scenarios, where HW is headwater elevation, TW is tailwater elevation, Q and Q_T denote total discharge, Q_c is culvert discharge, and Q_o is overtopping discharge.

3.2 Mapping Challenges

Inundation mapping at road crossings based on 1D modelling results is typically produced through interpolation of water surface elevations between the upstream and downstream cross sections, which can produce incorrect mapping for overtopped road crossings where the downstream tailwater level is significantly lower than the road crest. Figure 5 shows the modelled flood conditions at the 38 Avenue crossing in Stettler as an example. Because the tailwater level was too low, the interpolated water surface across the road embankment fell below the road crest. As a result, the map incorrectly shows no/partially overtopping at this road crossing, even though the hydraulic model indicated overtopping.

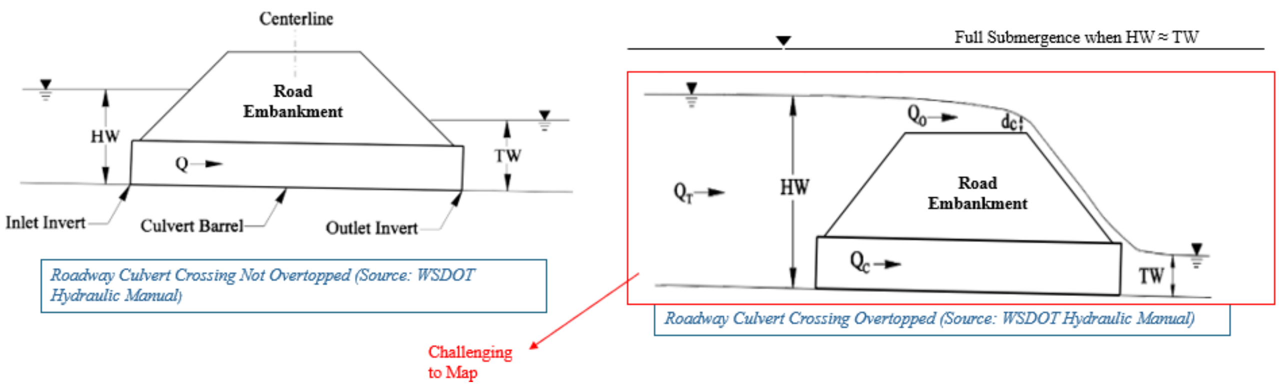

Figure 4: Submerged culvert hydraulics without and with road overtopping (Source: WSDOT, 2025)

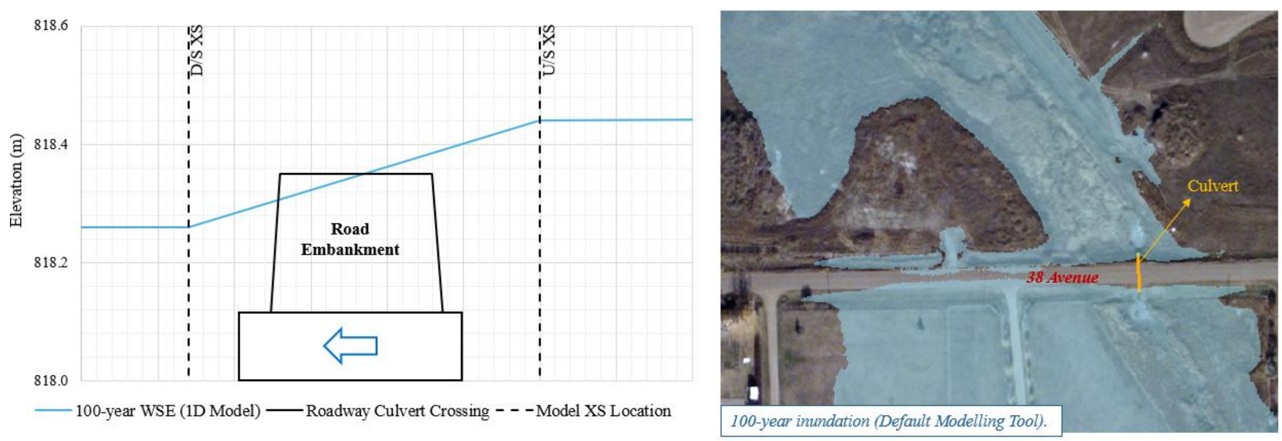

Figure 5: Roadway culvert overtopping mapping using standard modelling and mapping tools

3.3 Hydraulic Modelling and GIS Integration

The Stettler Flood Study used an integrated hydraulic modelling and GIS approach to accurately map roadway overtopping. Overtopping was identified in the model by weir flows, and at each identified location, a breakline was added at the downstream road edge with the upstream water level assigned (Figure 6). A modified water-surface TIN was created from cross sections and the breakline, then converted to elevation and depth raster to generate inundation polygons. This ensured the water surface remained high across the road crest for accurate overtopping representation.

3.4 Improved Inundation Mapping

The proposed approach produced an improved inundation map for the 38 Avenue crossing in Stettler, Alberta (Figure 6), providing more accurate delineation of inundation extents and road overtopping and greater efficiency than manual editing, particularly in areas with numerous culvert crossings. Using this method, flood depths computed on the downstream side of the roadway embankment (Figure 6) may be overestimated. However, this limitation has minimal effect on overall flood mapping, as this localized area does not typically influence hazard delineation, floodplain interpretation, or emergency planning decisions.

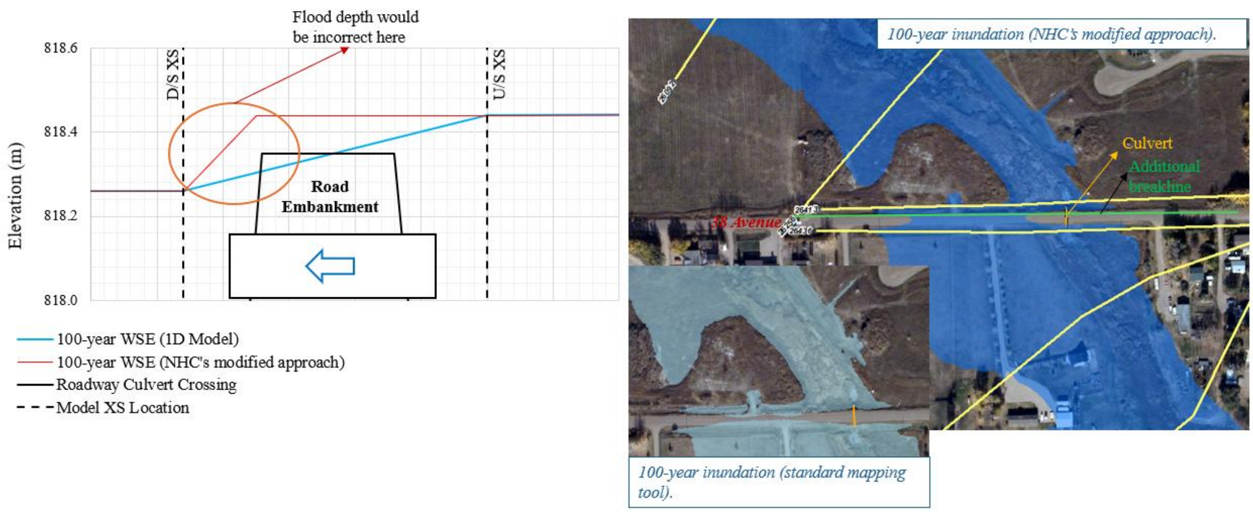

Figure 6: Improved flood mapping adopting the advanced integrated approach

4 CONCLUSION

This paper highlights two main challenges in flood mapping studies for small prairie streams, using the Stettler Flood Study as an example. First, it addresses the difficulty of developing flood hydrology in a flat prairie basin with limited data and significant basin and floodplain storage capacity. The results illustrate the importance of accounting for site-specific conditions, basin storage, and floodplain detention for more accurate flood frequency estimates and reliable inundation mapping. Second, it demonstrates the challenge of mapping roadway overtopping at culvert crossings with large differences between headwater and tailwater levels. A GIS processing approach was developed to resolve this issue, providing more accurate overtopping representation than the standard linear interpolation approach. Together, these hydrologic and mapping approaches improved floodplain mapping in the Stettler Flood Study.

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