28 June 2017

HIGHWOOD RIVER

Channel Stability Assessment

Submitted to:

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REPORT

Report Number: 1536669.7000_Rev.0

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Executive Summary

Alberta Environment and Parks (AEP) commissioned Golder Associates Ltd. (Golder) in September 2015 to undertake the Highwood River Hazard Study. The study area includes the communities of the Municipal District of Foothills, the Town of High River, and Village of Longview. The primary purpose of the study is to assess and identify river and flood hazards along the Highwood River from a location upstream of Longview to the Bow River confluence and along an upstream reach of the Little Bow River.

The study area is divided to nine (9) reaches for hydraulic modelling, including seven (7) along Highwood River and two (2) along Little Bow River as shown in Table i. Reach 5 was split into two sub-reaches for the channel stability analysis based on their differences in geomorphological characteristics.

Table i: River Reaches within Study Area

Reach Number	River	Reach Description	Length	Marker Posts (km)
1	Highwood River	Sheep River to Bow River Confluence	14.2	0 to 14.2
2		Tongue Creek to Sheep River	21.9	14.2 to 36.1
3		High River to Tongue Creek	7.0	36.1 to 43.1
4		High River	10.1	43.1 to 53.2
5a		Km 64 to High River	10.8	53.2 to 64.0
5b		Pekisko Creek to Km 64	13.3	64.0 to 77.3
6		Upstream Boundary of Study Area to Pekisko Creek	16.2	77.3 to 93.5
7	Little Bow River	Lower Reach	10.6	1.9 to 12.5
8		Upper Reach	1.9	0 to 1.9

The Channel Stability Assessment was conducted as part of the Highwood River Hazard Study. It includes the following four tasks:

- channel bank delineation and comparison
- cross-section comparison
- thalweg comparison
- rating curve comparison

The channel bank delineation and comparison was completed by delineating the banks and mapping river features in both historical and modern imagery datasets. The cross-section and thalweg comparisons were completed by conducting both qualitative and quantitative analyses. Due to the lack of historical cross-section and thalweg data for kilometres 0 to 30 and 63 to 93 on Highwood River and all of Little Bow River, only a qualitative assessment was conducted on the available 2016 river geometry data. For the rating curve comparison, the historical and current rating curves for the WSC gauge locations within the study area were compared relative to observed

changes in the river thalweg and features of the nearest river cross sections. The data collected from the comparison of river geometry (i.e., channel bank delineation, cross-section, and thalweg) was used to inform the interpretations of changes observed in the rating curves.

This report documents the methodology and results of the channel stability investigation, including qualitative and limited quantitative information about general channel stability along the study reaches.

Highwood River

Reach 1

The most downstream reach of Highwood River, Reach 1, is categorized as a sinuous, single channel river reach confined within a larger incised channel (suspected glacial outwash channel).

Visual evidence in the form of an increase in the occurrence of point and side bars from the aerial imagery suggests that Sheep River is a major contributor of sediment to Highwood River. As such, Reach 1 which is downstream of the Sheep River confluence contains more sediment than Reach 2, appears to have more active bars. Significant lateral migration at the Bow River confluence and the presence of active bars and migrating forested islands suggests that the very lowest section of Reach 1 is unstable.

Due to the confined nature of the channel within this reach, limited lateral migration is occurring. While narrowing of the channel in this reach was observed in the cross-section data, the change is not statistically significant. Due to the confined nature of the channel and limited lateral migration, this reach is considered predominantly stable with the exception of the section immediately upstream of the Bow River confluence.

The surface water elevations associated with the 2013 flood event overtopped the channel banks along this reach. However, based on the morphological data reviewed, it appears that the capacity of the river to handle discharge has not changed over the extent of historical data reviewed.

Reach 2

Reach 2 of Highwood River is categorized as a sinuous, single channel river reach confined within a larger incised channel (suspected glacial outwash channel).

Evidence for narrowing and down-cutting of the channel observed in the cross-section data, is considered to be statistically significant. The narrowing of the channel over time is possibly a result of land use changes and limitation of channel adjustment by river training (based on air photo observations of the channel planform) or diversion of Highwood River flow into Little Bow River, therefore reducing the average discharge of Highwood River.

Evidence for down-cutting was observed within the section of Reach 2 upstream of the Highway 2 Bridge crossing. Changes to the channel geometry along Reach 2 may be the result of changes in the thalweg elevation occurring slightly upstream of this reach. The down-cutting along the upstream section of Reach 2 inferred by the overall lowering of the thalweg may be the result of the river attempting to increase the gradient along this reach which has a gentle slope along its upstream end and a steeper slope at the downstream end leading to a convex-upwards profile through the reach.

While the narrowing and down-cutting along Reach 2 are considered to be statistically significant, due to the confined nature of the channel and limited lateral migration, this reach is considered to be stable. The 2013 flood event did not overtop the channel banks along this reach.

Reach 3

Reach 3 of Highwood River is characterized as a sinuous and single channel river reach. It differentiates from Reaches 1 and 2 in that it is not contained within the larger confined channel and has a very shallow slope with a net bed accretion occurring between km 38 and km 40.

The net bed change along this reach is estimated to be 2,216 m^3 based on an analysis of the thalweg data. However, in the cross-section comparison, only one of the five cross-sections along Reach 3 showed a shallowing of the bed. The other four cross-sections showed a deepening of the bed. The 1992 thalweg shows a small, localized basin in this area and therefore some of the net bed accretion may be attributed to its infilling. The longitudinal shape of the thalweg along this reach suggests instability, due to its concave-upwards profile.

The observed accretion suggests that the river is attempting to increase the slope along this reach to return to a more equilibrium profile and to return the longitudinal shape of the thalweg towards a concave-upward profile that can maintain competent sediment transport along the river. This sediment accretion is likely to be ongoing and would typically result in increased flood hazard with time through Reach 3 as the riverbed aggrades as a whole to increase local streambed gradient.

Reach 4

Reach 4 of Highwood River is characterized as a sinuous, tortuous sometimes single channel and sometimes multi-thread channel in a broad floodplain with actively migrating side, point and mid-channel bars. Relict oxbow channels can be seen in the aerial photography suggesting a highly mobile channel. Reach 4 has a slope of 0.0011, which is more shallowly sloped than Reaches 1, 2, 5a, 5b and 6 but is steeper than Reach 3.

This reach has an estimated net bed loss of -695 m^3 based on an analysis of the thalweg data. As a highly mobile channel with active bars, Reach 4 is considered to be unstable. However, as changes to channel geometry over time are not statistically significant, it is not suspected that the capacity of the river to handle discharge has changed.

Reach 5a

Reach 5a of Highwood River is similar to Reach 4 and is characterized as a sinuous, tortuous sometimes single channel and sometimes multi-thread channel in a broad floodplain with actively migrating side, point and mid-channel bars. As such, it may be considered an anastomosing reach due to its forested islands, multi-channeled sections and historical indications of avulsion.

Reach 5a has a slope of 0.0031, which is steeper that the slope of Reaches 1,2,3 and 4, and shallower than Reaches 5b and 6. This reach has an estimated net bed loss of -1,809 m^3 based on analysis of the thalweg data. Changes to the average bankfull depth along Reach 5a are considered statistically significant.

As a highly mobile channel with active bars, Reach 5a is considered to be unstable. However, as the channel has undergone a statistically significant deepening with a negative net bed change, it is estimated that the capacity of the river to handle discharge has increased and therefore improved the ability of the river to convey flood discharge.

Reaches 5b and 6

The upper reaches of Highwood River (i.e., Reaches 5b and 6) are characterized as single channel reaches with intermittent braiding within a deeply incised and confined larger channel. They are both categorized as having low sinuosity (sinuosity ≤ 1.3) and limited lateral migration was observed. Some stabilization of side and point bars was observed. Based on these observations, Reaches 5b and 6 are considered to be stable.

The water surface elevations associated with the 2013 flood event did not overtop the channel banks along these reaches.

Little Bow River

The lower and upper reaches of Little Bow River (i.e., Reaches 7 and 8) are characterized as single channel reaches.

Reach 8, the upper reach, is confined due to the presence of river training and diking along its full length and has a low sinuosity (sinuosity <1.3). No in-channel bars are present along this reach suggesting little to no sediment transport. This reach does not appear to have any obvious surface headwater sources, excluding the constructed diversion canal at the Town of High River.

The lower reach, Reach 7, is a partially confined and sinuous reach in a larger, more deeply incised valley suggestive of a larger river. Some mid-channel, point and side bars are present but do not appear to be active in terms of downstream migration and many historical side and point bars have stabilized into channel banks.

The thalweg for both the upper and lower reaches varies with several increases in elevation visible along its length. Based on the varying thalweg, lack of sediment transport and evidence of limited flow, Little Bow River, is estimated to be either a non-alluvial channel or confined within a geologically historical river valley (e.g., meltwater channel) and therefore the present undulating thalweg may be a relict feature.

Based on these observations, the Little Bow River is considered to be stable along the full length within the study area.

Acknowledgements

This component of the Highwood River Hazard Study (i.e., channel stability assessment) was managed by Morgan Tidd and Hua Zhang. Overall direction and senior review for this component was provided by Rowland Atkins, Hua Zhang and Dejiang Long. The channel stability assessment was conducted primarily by Morgan Tidd with support from Gaven Tang, Jie Chen, Vanessa Vallis and Peter Thiede.

The authors express their special thanks to Jim Choles and Muhammad Durrani, Project Managers of Alberta Environment and Parks, who provided overall project direction, background data and technical guidance.

The authors express their thanks to Dennis Lazowski with the Water Survey of Canada for supply of additional background information.

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APPENDICES

APPENDIX A
Cross-Section Comparisons

1.0 INTRODUCTION

1.1 Study Objectives

Alberta Environment and Parks (AEP) commissioned Golder Associates Ltd. (Golder) in September 2015 to undertake the Highwood River Hazard Study. The primary purpose of the study is to assess and identify river and flood hazards along the Highwood River from a location upstream of Longview to the Bow River confluence and along an upstream reach of the Little Bow River.

The study is conducted under the provincial Flood Hazard Identification Program (FHIP). The goals of the Program include enhancement of public safety and reduction of future flood damages through the identification of river and flood hazards. Project stakeholders include the provincial government, local authorities and the public.

The Highwood River Hazard Study includes multiple components and deliverables. This report documents the methodology and results of the channel stability investigation, including qualitative and limited quantitative information about general channel stability along the study reaches.

1.2 Study Reaches

The study area includes approximately 93 km of the Highwood River from a location upstream of Longview to the Bow River confluence, and approximately 13 km of the Little Bow River from High River to a location downstream of Highway 2 (see Figure 1).

The study area includes the communities in the Municipal District of Foothills, the Town of High River, and Village of Longview. The study area is divided to nine (9) reaches for hydraulic modelling, including seven (7) along Highwood River and two (2) along Little Bow River as shown in Table 1 and Figure 2a through 2e. Reach 5 was split into two sub-reaches for the channel stability analysis based on their differences in geomorphological characteristics.

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8		Upper Reach	1.9	0 to 1.9

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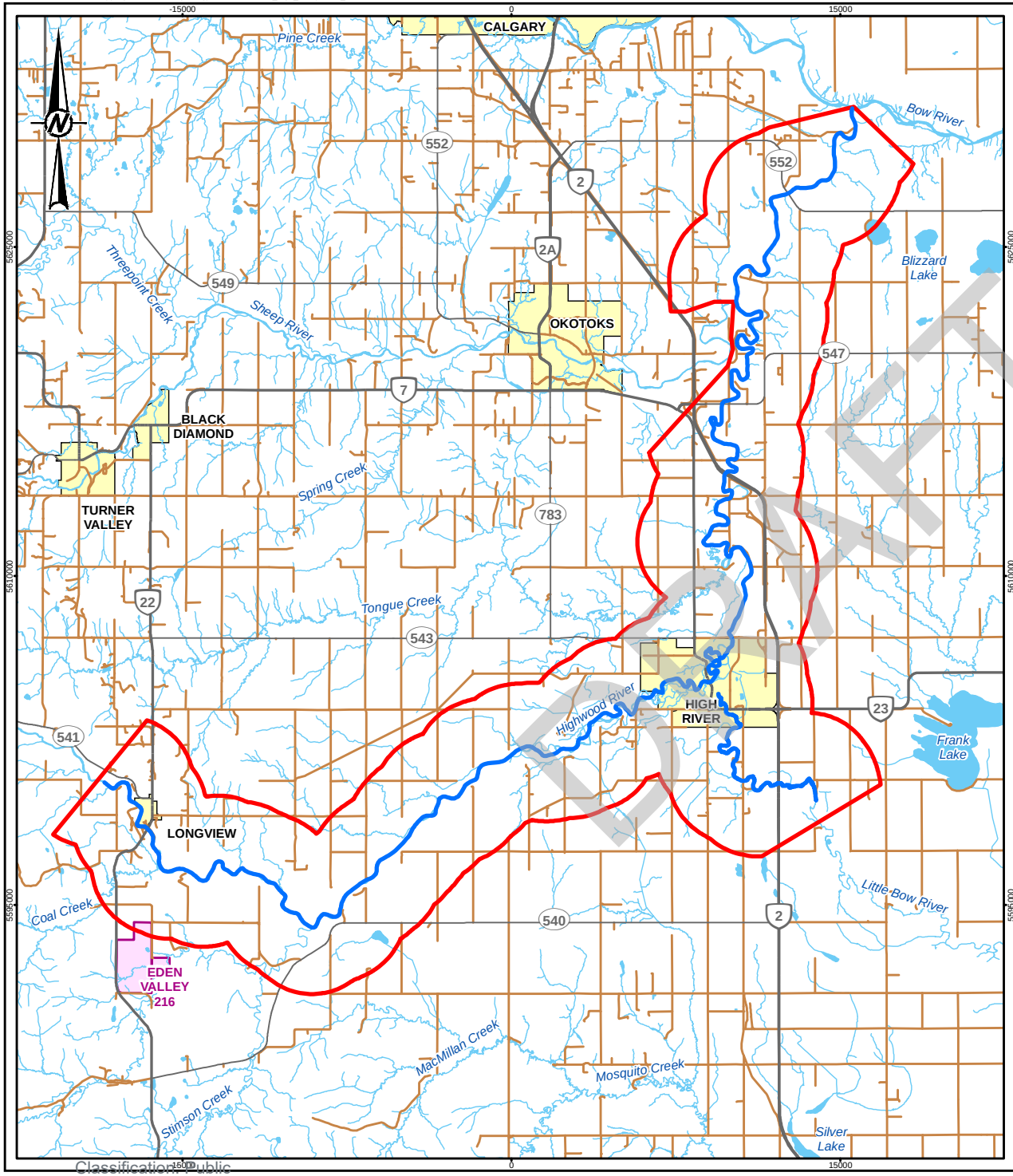

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- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- LOCAL ROAD
- WATERCOURSE
- WATERBODY
- INDIAN RESERVE
- POPULATED PLACE
- SURVEY REACH
- RIVER HAZARD STUDY AREA

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PROJECT
HIGHWOOD RIVER HAZARD STUDY

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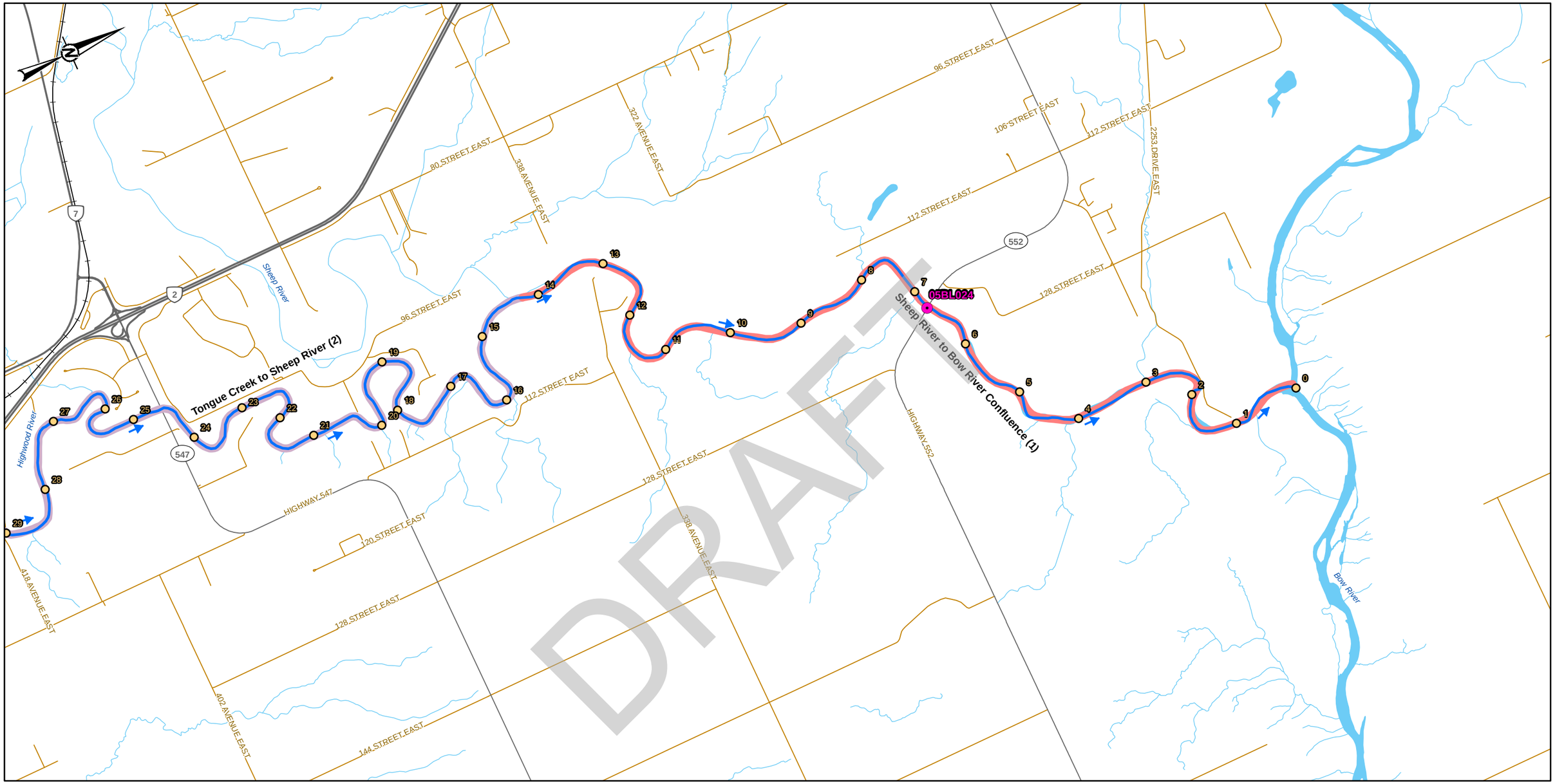

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- WATERBODY
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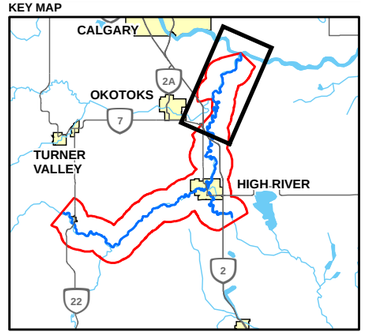
- RIVER STATION POST
- WATER SURVEY OF CANADA GAUGING STATION
- RIVER THALWEG
- CROSS SECTION LOCATION

RIVER REACHES

- SHEEP RIVER TO BOW RIVER CONFLUENCE (1)
- TONGUE CREEK TO SHEEP RIVER (2)
- HIGH RIVER TO TONGUE CREEK (3)
- HIGH RIVER (4)
- PEKISKO CREEK TO HIGH RIVER (5a)
- PEKISKO CREEK TO HIGH RIVER (5b)
- UPSTREAM BOUNDARY TO PEKISKO CREEK (6)
- LITTLE BOW LOWER REACH (7)
- LITTLE BOW UPPER REACH (8)

KEY MAP



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HIGHWOOD RIVER - SHEEP RIVER TO BOW RIVER CONFLUENCE

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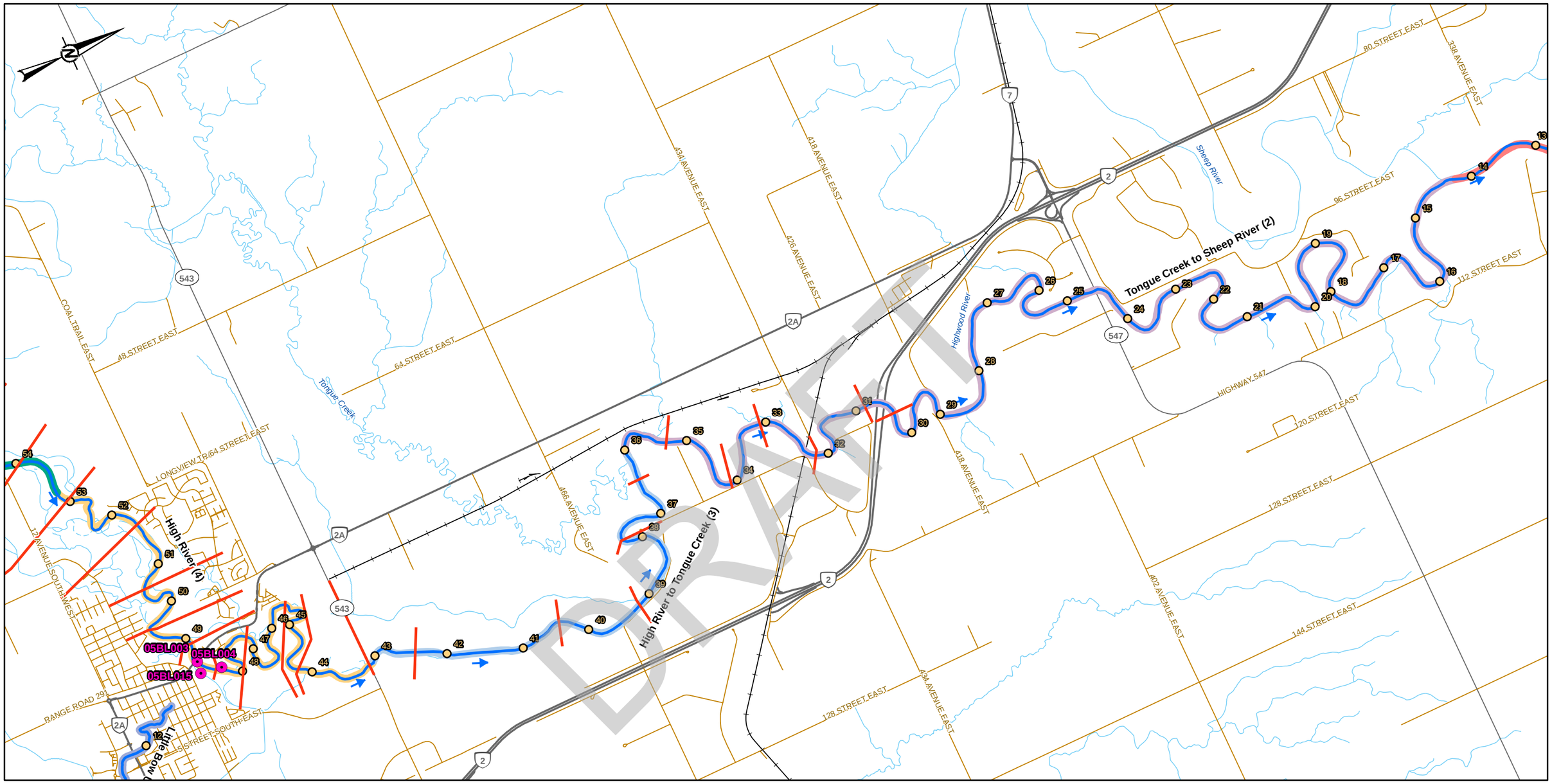

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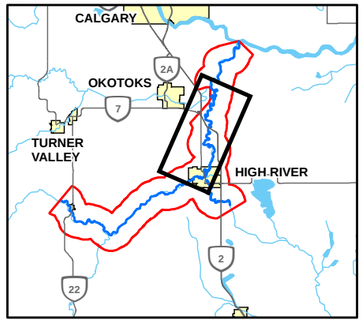

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HIGHWOOD RIVER - TONGUE CREEK TO SHEEP RIVER, HIGH RIVER TO TONGUE CREEK AND HIGH RIVER

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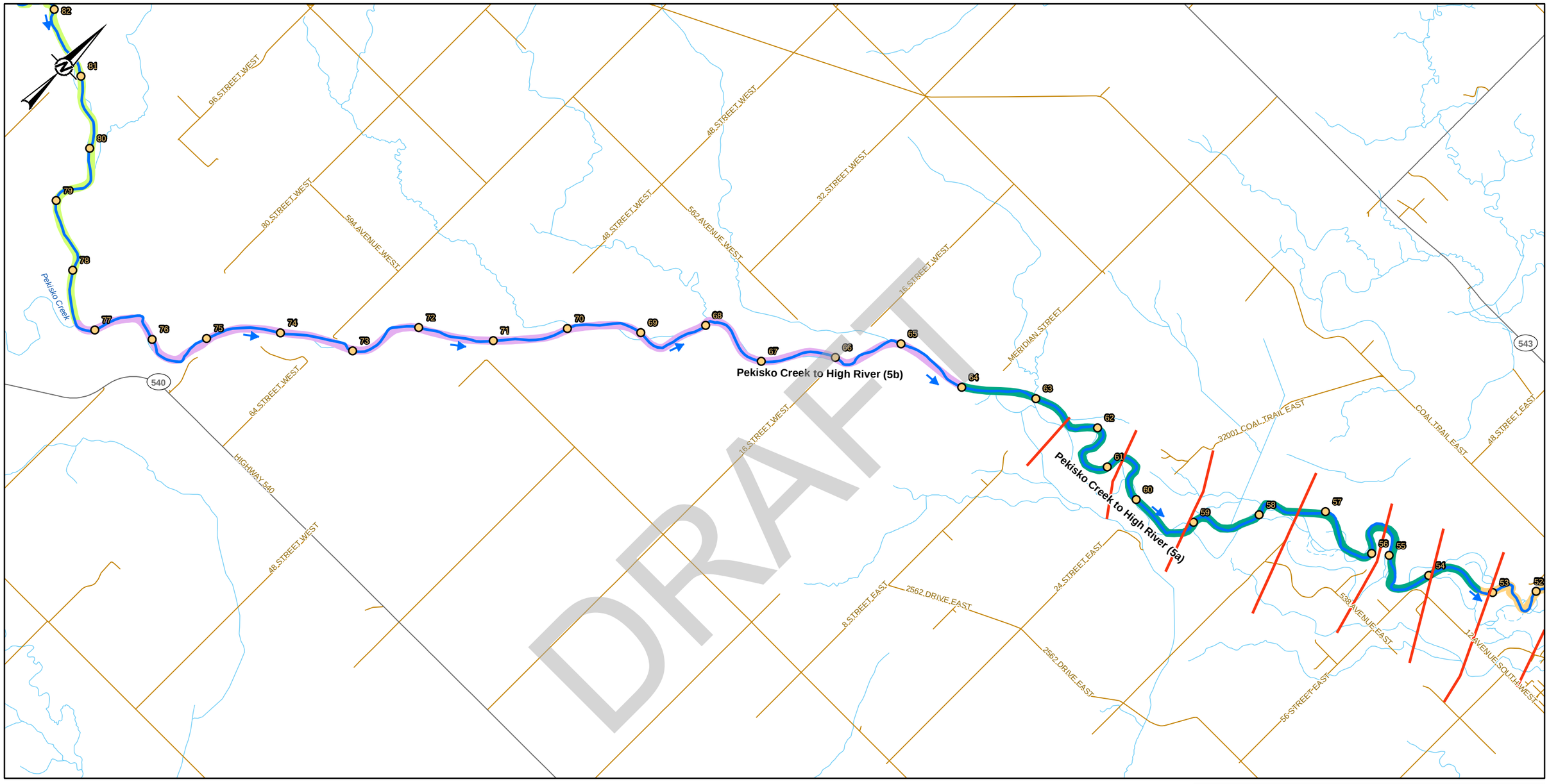

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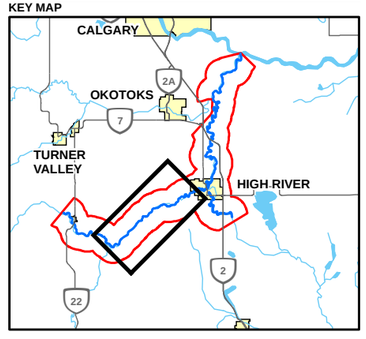

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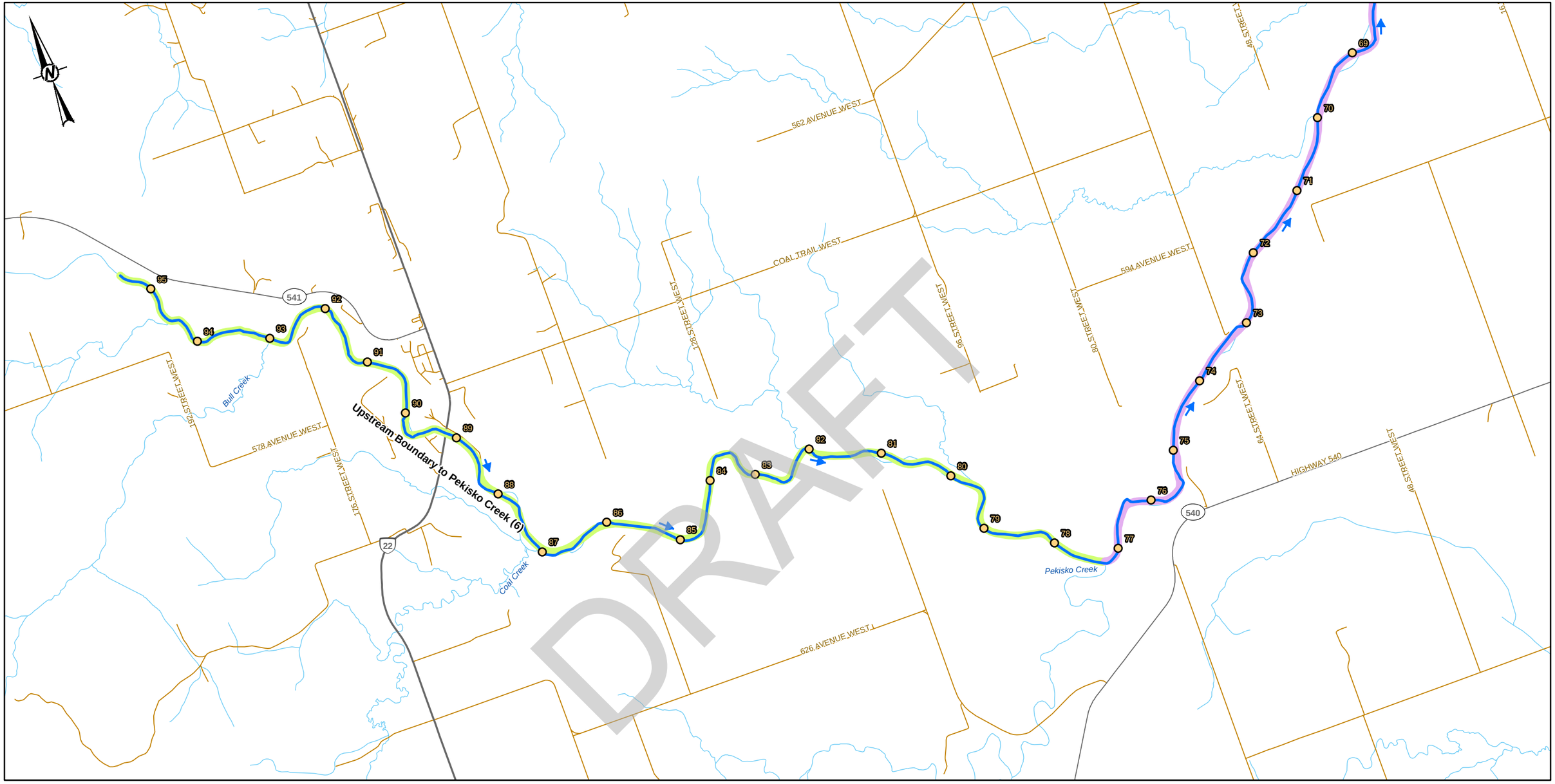

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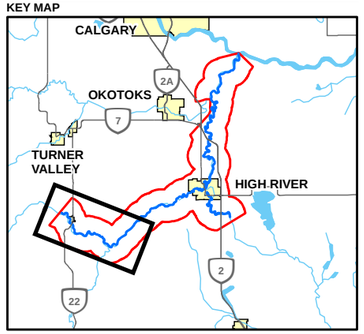

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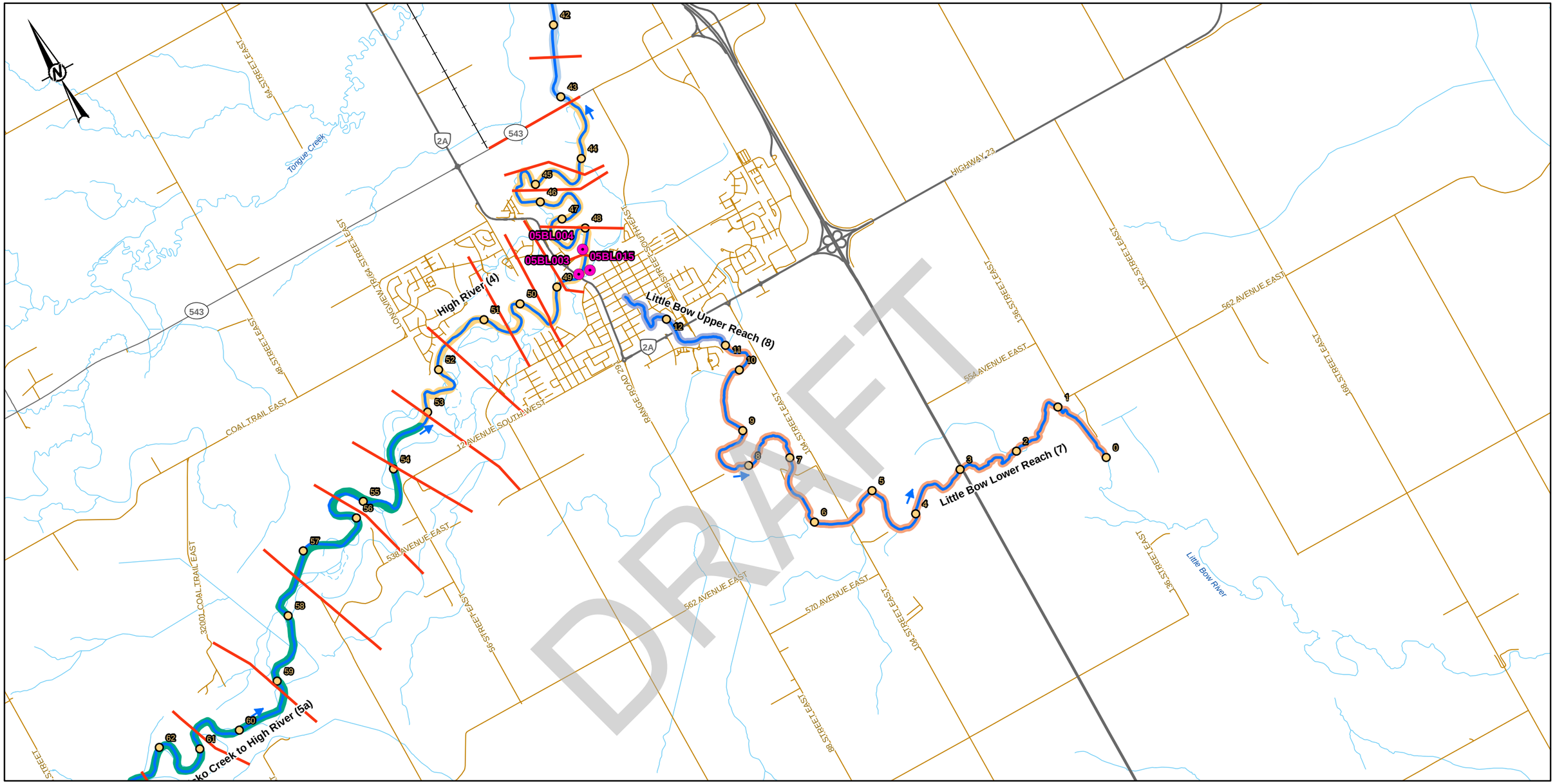


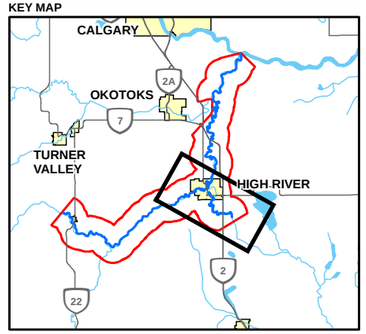
LEGEND

- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- LOCAL ROAD
- WATERCOURSE
- CHANNEL MIGRATION
- WATERBODY
- FLOW DIRECTION
- RIVER STATION POST
- WATER SURVEY OF CANADA GAUGING STATION
- RIVER THALWEG
- CROSS SECTION LOCATION

RIVER REACHES

- SHEEP RIVER TO BOW RIVER CONFLUENCE (1)
- TONGUE CREEK TO SHEEP RIVER (2)
- HIGH RIVER TO TONGUE CREEK (3)
- HIGH RIVER (4)
- PEKISKO CREEK TO HIGH RIVER (5a)
- PEKISKO CREEK TO HIGH RIVER (5b)
- UPSTREAM BOUNDARY TO PEKISKO CREEK (6)
- LITTLE BOW LOWER REACH (7)
- LITTLE BOW UPPER REACH (8)

KEY MAP



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CLIENT
ALBERTA ENVIRONMENT AND PARKS

PROJECT
HIGHWOOD RIVER HAZARD STUDY

TITLE
LITTLE BOW RIVER - LOWER REACH AND UPPER REACH

CONSULTANT
Golder Associates

YYYY-MM-DD	2017-06-28
DESIGNED	MT
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APPROVED	HZ

PROJECT NO.	CONTROL	REV.	FIGURE
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1.3 Work Scope

The scope of the channel stability investigation includes the following:

- Historical Aerial Photography Preparation.
- Channel Bank Delineation and Comparison:
  - Identification and comparison of the most recent and historical channel banks to establish representative illustrative bank stability and instability conditions in the study area.
- Cross Section Comparison:
  - Comparison of the available historical and current main channel cross sections along the study reaches.
- Thalweg Profile Comparison:
  - Comparison of the most recent thalweg profile and any available historical thalweg profiles to identify any changes.
- Gauge Rating Curve Comparison:
  - Comparison of the river gauge rating curves and evaluation of any rating curve changes.

2.0 AVAILABLE DATA

2.1 Aerial Imagery

Aerial imagery available for this study was for a historical dataset which consisted of 1950 and 1951 images and a current dataset collected in 2016. Table 2 provides a summary of the dates, scale, resolution, source and accuracy of the aerial imagery datasets used for the channel bank delineation and comparison. Details of the methods and results for the aerial photography preparation are provided in the following technical memorandums:

- 2016 Aerial Imagery Acquisition Memorandum – Highwood River Hazard Study (Golder Document: 1536669_2016Aerial_Imagery_Collection_memo_24Nov2016_Unsecured.pdf)
- Historical Aerial Imagery Processing - Highwood River Hazard Study (Golder Document: 1536669_Historical_Imagery_memo_10Jan2017.pdf)

Table 2: Summary of Aerial Imagery

	Date(s) of Collection	Scale	Resolution	Source	Accuracy
Current	5/30/2016	1:15,000	0.30 m	Geodesy Group Inc. and Golder (2016a)	Horizontal = 0.6 m Vertical = 1.0 m
Historical	4/30/1950, 5/12/1950, 5/7/1951	1:40,000	0.80 m	AEP (Golder2017)	±5 m

2.2 Cross-Section Data

Cross-section data was available from the 1992 HEC-2 model, two sets of LiDAR data (2013 and 2015), 2016 survey data, and 2016 aerial imagery. Table 3 provides a summary of the dates, scale, resolution, source and accuracy of the datasets used for the cross-section comparison.

Historical cross-section data (1992) was not available for Highwood River for kilometres 0 to 30 and 63 through 93 or the entire Little Bow River section (0 to 13 km). Therefore, a comparison along these sections could not be conducted. Where historical data was missing, a quantitative review of the available 2016 river geometry (e.g., width and/or depth) was undertaken without comparison to other years.

Table 3: Summary of Cross-Section Data

	Date(s) of Collection	Scale [1]	Resolution	Source	Accuracy
1992 Model	10/1990	1:5,000	Unknown	AEP	unknown
2013 LiDAR	Fall 2013, post-flood	1:1	0.50 m	AEP	Horizontal and vertical ±0.15 m
2015 LiDAR	4/10/2015 to 4/19/2015	1:1	0.50 m	AEP	Horizontal and vertical ±0.15 m
2016 Survey	10/2013, 8/2015 to 11/2015. 4/2016 to 9/2016	--	--	Golder 2016b	RTK = ±0.02 m horizontal and vertical, ADP = ±0.10 m horizontal and vertical

Note:

A map scale is defined as the amount of reduction between the real world and its graphic representation. As LiDAR files are measurements of the real world, they have a scale of 1:1.

2.3 Thalweg Profile Data

Thalweg data was available from the 1992 HEC-2 model, two sets of LiDAR data (2013 and 2015), 2016 survey data and 2016 aerial imagery. Table 4 provides a summary of the dates, scale, resolution, source and accuracy of the datasets used for the thalweg comparison.

Historical thalweg data (1992) was not available for Highwood River for kilometres 0 to 30 and 63 through 93 or the entire Little Bow River section (0 to 13 km). Therefore, a comparison along these sections could not be conducted. Where historical data was missing, a qualitative review of only 2016 river thalweg data was undertaken. Details of the methods and results of the 2016 survey data are presented in the 2016 Golder Draft Highwood River Hazard Study Survey and Base Data Collection Report (Golder Document No. 1536669_R0001 Rev. A).

Table 4: Summary of Thalweg Profile Data

	Date(s) of Collection	Scale	Resolution	Source	Accuracy
1992 Model	10/1990	1:5,000	Unknown	AEP	unknown
2013 LiDAR	Fall 2013, post-flood	1:1	0.50 m	AEP	Horizontal and vertical ±0.15 m
2015 LiDAR	4/10/2015 to 4/19/2015	1:1	0.50 m	AEP	Horizontal and vertical ±0.15 m
2016 Survey	10/2013, 8/2015 to 11/2015, 4/2016 to 9/2016	--	--	Golder 2016	RTK = ±0.02 m horizontal and vertical, ADP = ±0.10 m horizontal and vertical.
2016 Aerial Imagery	5/30/2016	1:15,000	0.30 m	GeodesyGroup Inc. and Golder	Vertical = 0.056 m

Scale Note – a map scale is defined as the amount of reduction between the real world and its graphic representation. As LiDAR files are measurements of the real world, they have a scale of 1:1.

2.4 Rating Curves

Discharge and water level data was provided by the Water Survey of Canada (2016) for the following three stations within the study area:

- Highwood River below Little Bow Canal (Station 05BL004)
- Highwood River near the Mouth (Station 05BL024)
- Little Bow Canal at High River (Station 05BL015)

Entire datasets were obtained for each station. The records obtained extend back to 1987, 1970 and 1923 for Highwood River below Little Bow Canal (Station 05BL004), Highwood River near the Mouth (Station 05BL024), and Little Bow Canal at High River (Station 05BL015), respectively. Rating curve comparisons for Highwood River below Little Bow Canal (Station 05BL004) and Highwood River near the Mouth (Station 05BL024) were based on only the oldest and youngest available datasets. No change in gauge location or survey datum was noted for these stations.

The record at Little Bow Canal covers the period from 1923 to present. However, the data prior to 1952 was insufficient to create rating curves. Between 1952 and 2003, the gauge was moved or replaced four times and therefore consisted of four different survey datums. Varying survey datums between rating curves limit direct interpretation of the relationship between changes in discharge and water level and the channels response to such changes. The data presented for the rating curve at Little Bow Canal includes 1952, 1954, 1975, 1984, 2003 and the most recent dataset from 2017 for comparison and discussion.

3.0 METHODS

3.1 Channel Bank Delineation and Comparison

The channel bank delineation and comparison were conducted in electronic format using ortho-rectified and geo-referenced (triangulated) historical air photos. Historical air photos were reviewed using stereo-pairs for use in mapping software (e.g., PurView™[1]). Coverage, resolution and scale of the imagery are discussed in Section 2.1.

Channel banks were delineated directly onscreen from the historical imagery (1949-1951) and from the most recent aerial imagery (2016). Bank delineation and major river features (e.g., single thread or multi-channel, major islands, sediment bars and/or significant secondary channels) were identified as they pertain to observed channel bank stability or instability. Once mapped in Purview™, the digital channel margins were exported into an ArcGIS 10.2 (ArcMap) database with the geospatial attributes.

A comparison of the historically-imaged and most-recently-imaged channel banks was undertaken with both channel bank lines depicted on the most recent photo base provided by AEP. A select set of figures was developed to highlight example areas of channel stability/instability. These figures are accompanied by a technical summary regarding the general nature of channel stability/instability in the study area (e.g., channel instability is highest on the downstream, outside portion of the major meanders).

3.2 Cross-Section Comparison

For the cross-section comparison, a preliminary analysis was carried out to identify an appropriate number of representative cross sections for comparison to provide adequate coverage and detail of the Highwood River Study Area. For the cross-section comparison, a subsample of representative cross sections was selected for review in detail. The selected representative cross sections were compared with estimates of meander spacing to validate coverage of the major river features. A total of 28 representative cross-sections were chosen within Highwood River Reaches 2, 3, 4 and 5.

Following identification of the representative cross sections, qualitative and quantitative analyses were completed. The qualitative analysis included review and documentation of cross-section features such as right-handedness or left-handedness (i.e., the deepest part on the left or right side of the river channel), skewness (i.e., cross section with a uniform geometry or leaning to left or right), single thread or multiple thread channels, and evidence of aggradation or degradation.

The quantitative analysis of channel geometry consisted of the estimation of cross-sectional area, maximum bankfull depth, bankfull width, and average bankfull depth. These parameters were used to determine channel type and changes in hydraulic capacity using hydraulic relationships. A high level statistical analysis was completed on the river geometry for each reach to determine the significance of recorded changes.

[1] Product of I.S.M. International Systemap Corp., distributed by ESRI in Canada (www.mypurview.com)

Due to the lack of historical cross-section data for kilometres 0 to 30 and 63 to 93 on Highwood River and all of Little Bow River reach, only a qualitative analysis was conducted on the available 2016 river geometry data and channel width from the historical channel bank delineation.

3.3 Thalweg Profile Comparison

The river thalweg is the line that passes through the deepest parts of the river in the downstream direction. It links the deepest areas of the river together and can be used as one of the representative features of channel geometry.

The historical and current thalweg profiles were compared. Interpreted increases or decreases in thalweg slope were evaluated and documented in the context of the reviewed cross sections and the major river features. Areas of scour (thalweg slope increase or elevation decrease) or sedimentation (thalweg slope decrease or elevation increase) were identified and the net bed change by reach was calculated.

Due to the lack of historical thalweg data for kilometres 0 to 30 and 63 to 93 on Highwood River and all of Little Bow River, only a qualitative assessment was conducted on the available 2016 river geometry data.

Historical thalweg data was available in profile view only. Therefore, a plan view comparison of the thalweg to evaluate channel migration was not completed. Migration of the river channel as documented in the channel bank and cross-section comparisons is deemed to be sufficient to address lateral migration of the river.

3.4 Rating Curve Comparison

Changes in riverbed elevation and thalweg may result in changes in the rating curve for a water level gauge. This is related to the passage of sediments through the river and the essentially mobile nature of the riverbed which may go up or down in response to river changes and flood events. Available rating curve data was provided by the Water Survey of Canada as described in Section 2.4.

The historical and current rating curves for the WSC gauge locations within the study area were compared relative to observed changes in the river thalweg and features of the nearest river cross sections. The data collected from the comparison of river geometry (i.e., channel bank delineation, cross-section, and thalweg) was used to inform the interpretations of changes observed in the rating curves.

4.0 RESULTS

4.1 Channel Bank Comparison

The results of the channel bank delineation and comparison are summarized in Table 5, and the representative sub-reaches are shown in Figure 3 through Figure 10. These results are described below:

- Reach 1 is typically defined by a stable planform with limited areas of instability. A representative portion of Reach 1 stable sub-reach is shown in Figure 3. This sub-reach shows limited lateral migration of the channel. Several point bars are present in both the historical and current datasets with more side bars present in the 2016 dataset. The observed historical point bars have typically expanded slightly and shifted slightly downstream to their current positions.

  A representative portion of Reach 1 unstable sub-reach is shown in Figure 3. This sub-reach is located near the confluence of the Highwood River to the Bow River. The channel has migrated substantially around two meander bends, shifting laterally from the centreline of the river by approximately 30 m to 80 m. The historical point bars have expanded in area, likely as the result of aggradation forcing the channel to shift laterally and erode the outside margins of the meander bends along this sub-reach.

  Several side bars and forested bars are present near the mouth of the river and have shifted over time. The mouth of Highwood River has also shifted approximately 50 m north, with a slight downstream deflection at the Bow River confluence.

- The representative sub-reaches along Reach 2 and Reach 3 are shown in Figure 4 and Figure 5. These entire reaches are considered to be stable. Unstable sub-reaches have not been included. These sub-reaches show minimal lateral migration of the channel with the main examples of lateral migration occurring along the bends of meanders. The sub-reach from Reach 2 is a meandering sub-reach while the sub-reach from Reach 3 is fairly straight. These reaches are characterized by limited lateral migration, small side bars and stabilization of previous forested islands and side bars.

- The representative sub-reach along Reach 4 is shown in Figure 6. This entire reach is considered to be unstable. A stable sub-reach has not been included. The sub-reach is a meandering river with significant lateral migration of the channel. Several relic oxbows are visible alongside the current channel suggesting substantial movement over time. Several side bars are visible in the historical and current datasets, suggesting mobile material.

- Representative sub-reaches for Reaches 5a and 5b are shown in Figure 7. The sub-reach for Reach 5a consists of tortuous and braided multi-thread channels characterized by the presence of numerous side, point and mid-channel bars. Several forested islands are present in both the historical and 2016 datasets.

  The river channel along the subreach has been realigned so that the historical alignment bears limited resemblance to the modern alignment. Due to the presence of several well established forested areas between the historical and current channel alignments with limited evidence of progressive channel shifts, this suggests that the realignment of the channel occurred during a sudden event, like an avulsion, rather than through progressive meander migration over time.

  Un-vegetated channels in the floodplain are also visible, suggesting a recent avulsion event like the 2013 flood. Reach 5a consists of many of these characteristics and is considered to be unstable.

- The sub-reaches for Reach 5b (Figure 7) and Reach 6 (Figure 8) show a slightly sinuous, wandering, braided river within an incised relict channel. Minimal lateral migration of the channel has occurred with the main examples of lateral migration occurring along the bends of meanders. Several historical and current side and mid-channel bars suggest moderate sediment transport downstream. The presence of several historical and current forested islands implies some stability within the channel.
- The sub-reaches along Little Bow River for Reach 7 (Figure 9) and Reach 8 (Figure 10) show a sinuous river within a slightly incised channel with limited sediment transport. Minimal lateral migration of the channel has occurred with the main occurrences of lateral migration being co-located along the bends of meanders and in the vicinity of man-made structures (i.e., bridges, dikes). Limited active side or point bars are present suggesting low sediment load.

  The upper reach of Little Bow River (Reach 8 shown in Figure 10) is within the urban environment of the Town of High River. The channel appears to be confined by diking since the 1950s. Approximately one kilometre of the historical channel has now disappeared under housing developments, as can be seen by the dashed historical alignment in Figure 10.

Table 5: Channel Bank Delineation Comparison

Reach	Representative Section Km	Figure	Description
1 - Sheep River to Bow River Confluence	6 – 8	Figure 3	- Confined - Incised - Presence of mid-channel and side bars - Stabilization of side bars resulting in the narrowing of the channel - Stable
	0 - 3		- Confined - Incised - Presence of mid-channel and side bars - Lateral migration of river mouth into Bow River - Unstable
2 - Tongue Creek to Sheep River	18 - 23	Figure 4	- Confined - Incised - Limited presence of mid-channel and side bars - Stabilization of side bars resulting in the narrowing of the channel
3 - High River to Tongue Creek	41 - 43	Figure 5	- Confined - Incised - Limited presence of mid-channel and side bars- Stabilization of side bars resulting in the narrowing of the channel
4 - High River	44 – 49	Figure 6	- Unconfined - Significant migration of channel meanders and complete realignment of main channel - Presence of mid-channel and side bars - Loss/migration of forested islands - New channels present
5a – Km 64 to High River	54 – 58	Figure 7	- Unconfined - Significant migration of channel meanders and complete realignment of main channel - Presence of mid-channel and side bars - Loss/migration of forested islands - New channels present
5b - Pekisko Creek to Km 64	72 - 74	Figure 7	- Confined - Incised - Presence of mid-channel and side bars - Stabilization of side bars resulting in the narrowing of the channel
6 - Upstream Boundary of Study Area to Pekisko Creek	92 – end.	Figure 8	- Confined - Incised - Presence of mid-channel and side bars - Stabilization of side bars resulting in the narrowing of the channel
7 - Little Bow Upper Reach	11 - end	Figure 9	- Little to no evidence of mid-channel and side bars - Limited evidence of lateral migration - Highly channelized
8 - Little Bow Lower Reach	8 – 9.5	Figure 10	- Confined - Incised - Limited presence of mid-channel and side bars - Stabilization of side bars resulting in the narrowing of the channel - Limited evidence of lateral migration

STABLE SUBREACH

Highwood River

UNSTABLE SUBREACH

Highwood River

LEGEND

- RIVER STATION POST
- FLOW DIRECTION
- RIGHT BANK (2016)
- RIGHT BANK HISTORICAL (1951)
- LEFT BANK (2016)
- LEFT BANK HISTORICAL (1951)
- CHANNEL BAR (2016)
- CHANNEL BAR HISTORICAL (1951)
- FORESTED ISLAND (2016)
- FORESTED ISLAND HISTORICAL (1951)
- PROTECTED BANK (2016)

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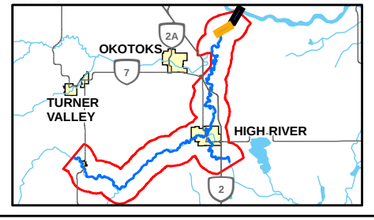
LEGEND KAY MAP

- STABLE SUBREACH
- UNSTABLE SUBREACH

KEY MAP



PROJECT
HIGHWOOD RIVER HAZARD STUDY

PROJECT
SHEEP RIVER TO BOW RIVER CONFLUENCE CHANNEL BANK COMPARISON - REPRESENTATIVE SUBREACHES

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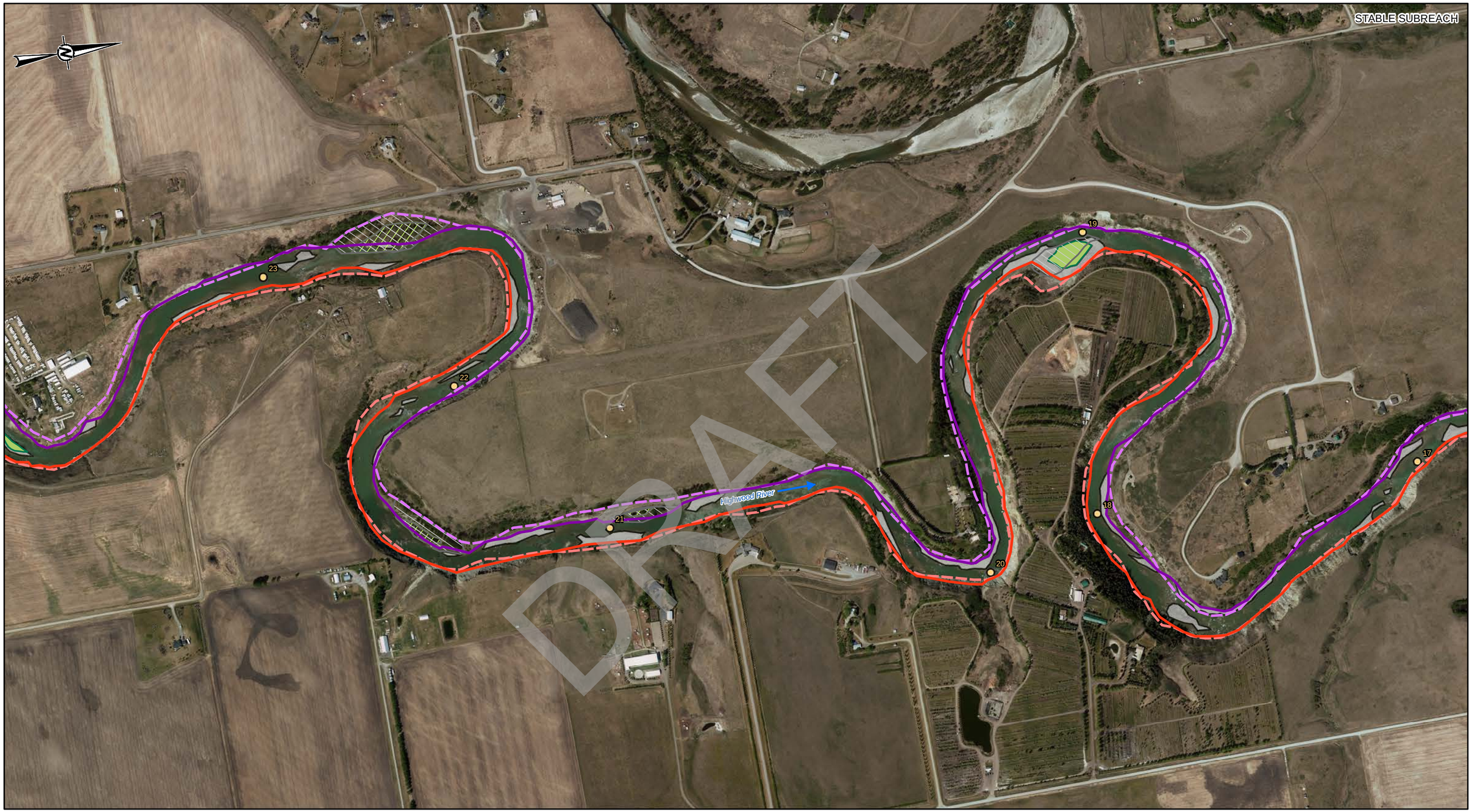

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- RIGHT BANK HISTORICAL (1951)
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- LEFT BANK HISTORICAL (1951)
- CHANNEL BAR (2016)
- CHANNEL BAR HISTORICAL (1951)
- FORESTED ISLAND (2016)
- FORESTED ISLAND HISTORICAL (1951)
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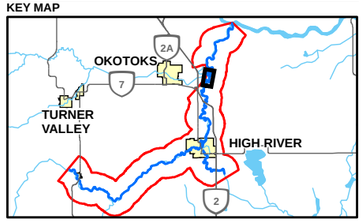
- STABLE SUBREACH
- UNSTABLE SUBREACH

KEY MAP



PROJECT
HIGHWOOD RIVER HAZARD STUDY

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TONGUE CREEK TO SHEEP RIVER CHANNEL BANK COMPARISON - REPRESENTATIVE SUBREACHES

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LEGEND

- RIVER STATION POST
- FLOW DIRECTION
- RIGHT BANK (2016)
- RIGHT BANK HISTORICAL (1951)
- LEFT BANK (2016)
- LEFT BANK HISTORICAL (1951)
- CHANNEL BAR (2016)
- CHANNEL BAR HISTORICAL (1951)
- FORESTED ISLAND (2016)
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- STABLE SUBREACH
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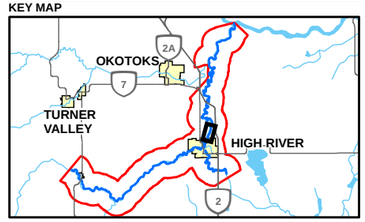

PROJECT
HIGHWOOD RIVER HAZARD STUDY

PROJECT
HIGH RIVER TO TONGUE CREEK CHANNEL BANK COMPARISON - REPRESENTATIVE SUBREACHES

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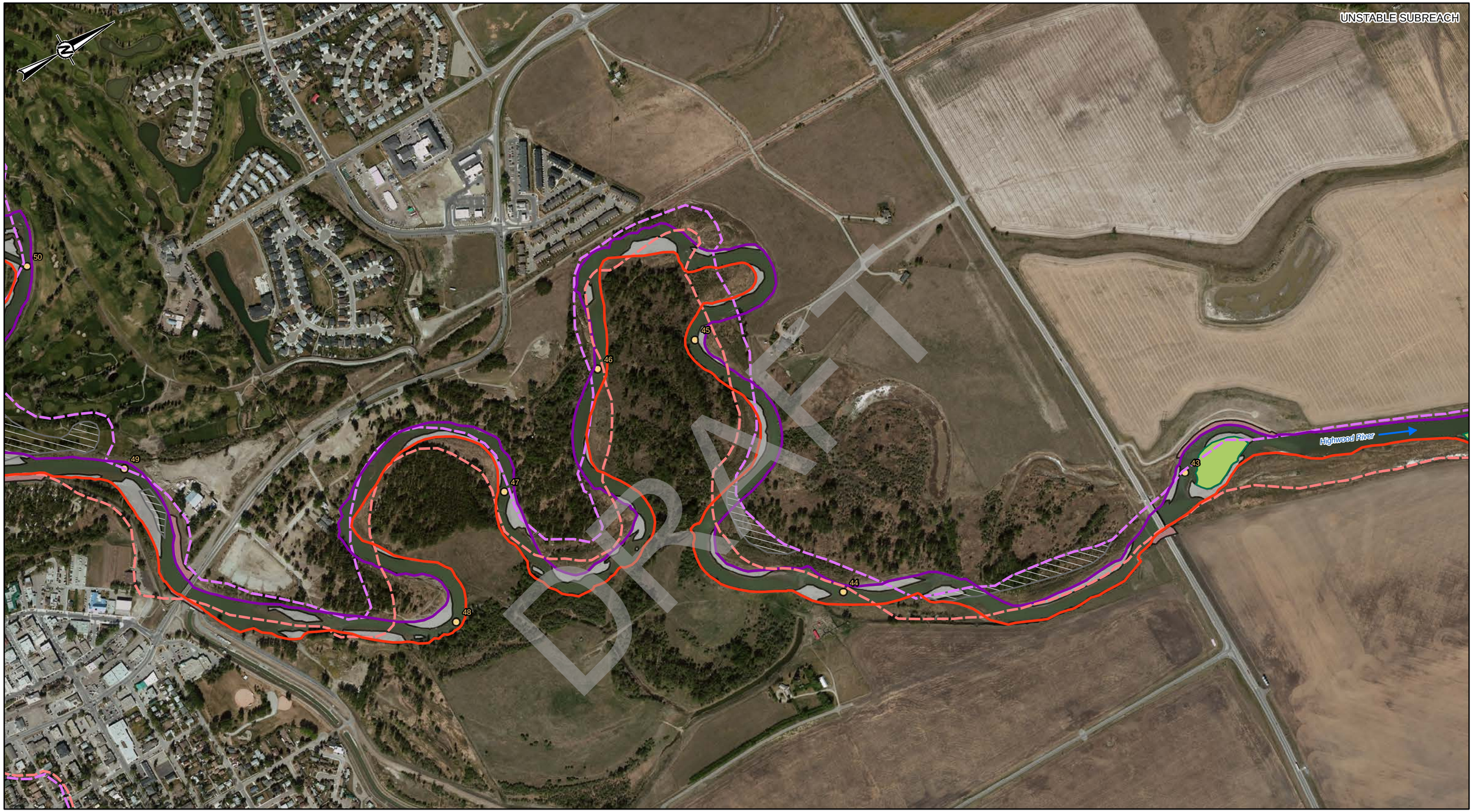

LEGEND

- RIVER STATION POST
- FLOW DIRECTION
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- RIGHT BANK HISTORICAL (1951)
- LEFT BANK (2016)
- LEFT BANK HISTORICAL (1951)
- CHANNEL BAR (2016)
- CHANNEL BAR HISTORICAL (1951)
- FORESTED ISLAND (2016)
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- STABLE SUBREACH
- UNSTABLE SUBREACH

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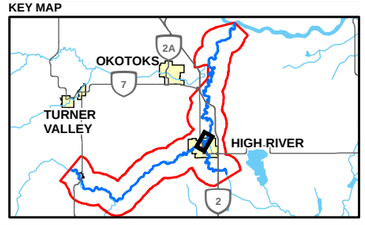

PROJECT
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PROJECT
HIGH RIVER CHANNEL BANK COMPARISON - REPRESENTATIVE SUBREACHES

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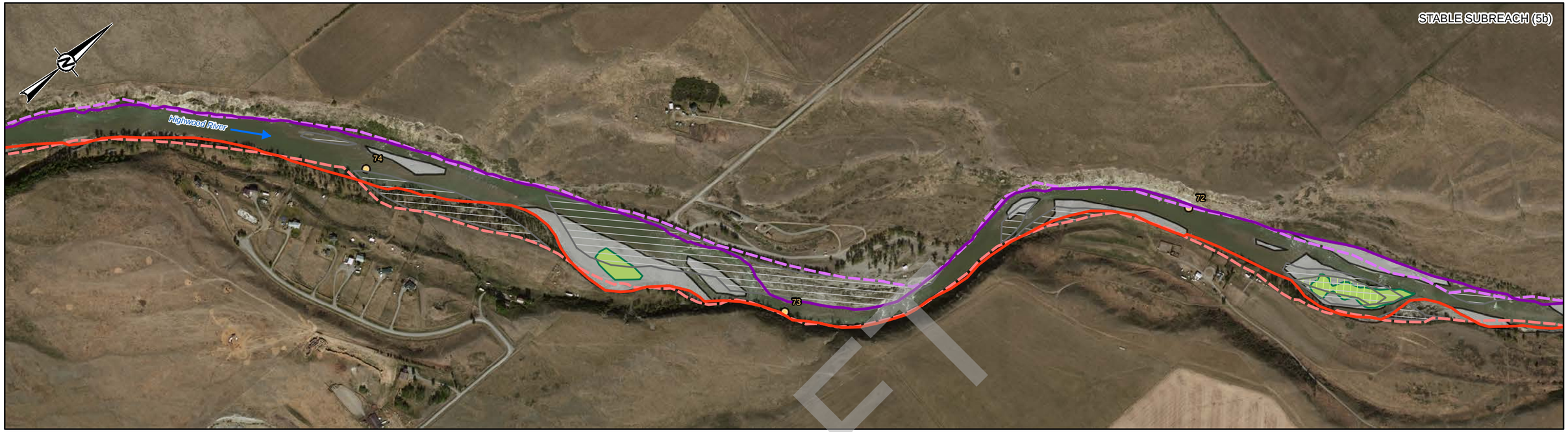

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- RIVER STATION POST
- FLOW DIRECTION
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- RIGHT BANK HISTORICAL (1951)
- LEFT BANK (2016)
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- CHANNEL BAR (2016)
- CHANNEL BAR HISTORICAL (1951)
- FORESTED ISLAND (2016)
- FORESTED ISLAND HISTORICAL (1951)
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LEGEND KAY MAP

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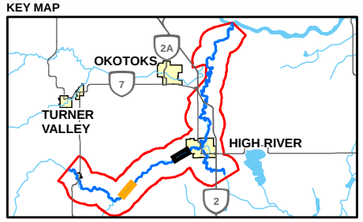
- UNSTABLE SUBREACH

KEY MAP



PROJECT
HIGHWOOD RIVER HAZARD STUDY

PROJECT
PEKISKO CREEK TO HIGH RIVER CHANNEL BANK COMPARISON - REPRESENTATIVE SUBREACHES

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DATUM: NAD 83 CSRS PROJECTION: 3TM 114

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CONSULTANT
Golder Associates

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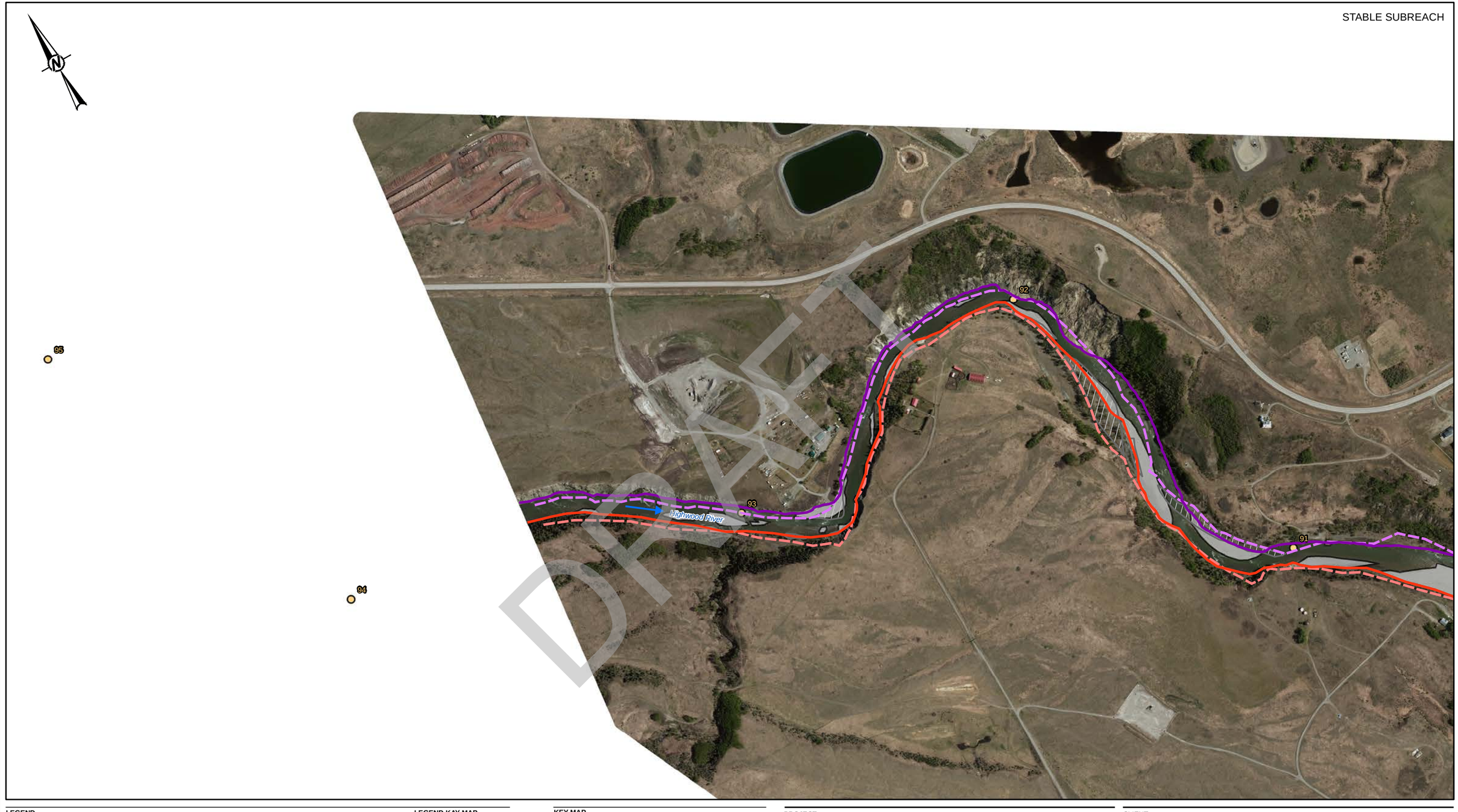
PREPARED	PT
REVIEWED	MT
APPROVED	HZ

PROJECT NO. 1536669 | CONTROL | REV. 0 | FIGURE 7



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- CHANNEL BAR HISTORICAL (1951)
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- FORESTED ISLAND HISTORICAL (1951)
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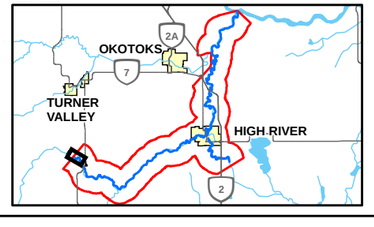
LEGEND KAY MAP

- STABLE SUBREACH
- UNSTABLE SUBREACH

KEY MAP



PROJECT
HIGHWOOD RIVER HAZARD STUDY

PROJECT
UPSTREAM BOUNDARY TO PEKISKO CREEK CHANNEL BANK COMPARISON - REPRESENTATIVE SUBREACHES

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APPROVED	HZ

PROJECT NO.	CONTROL	REV.	FIGURE
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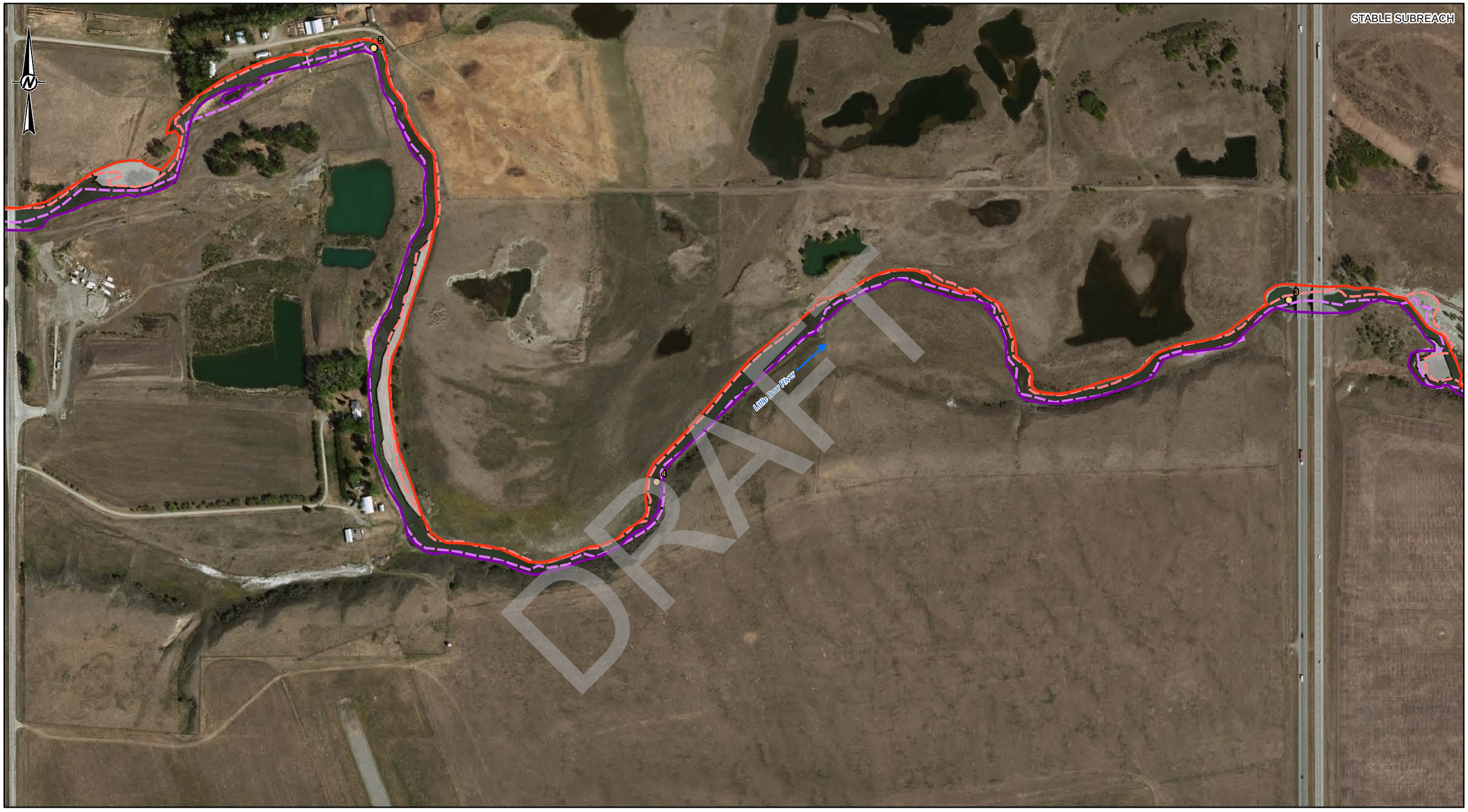

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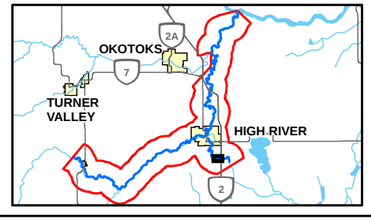

PROJECT
HIGHWOOD RIVER HAZARD STUDY

PROJECT
LITTLE BOW LOWER REACH CHANNEL BANK COMPARISON - REPRESENTATIVE SUBREACHES

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REVIEWED	MT
APPROVED	HZ

PROJECT NO.	CONTROL	REV.	FIGURE
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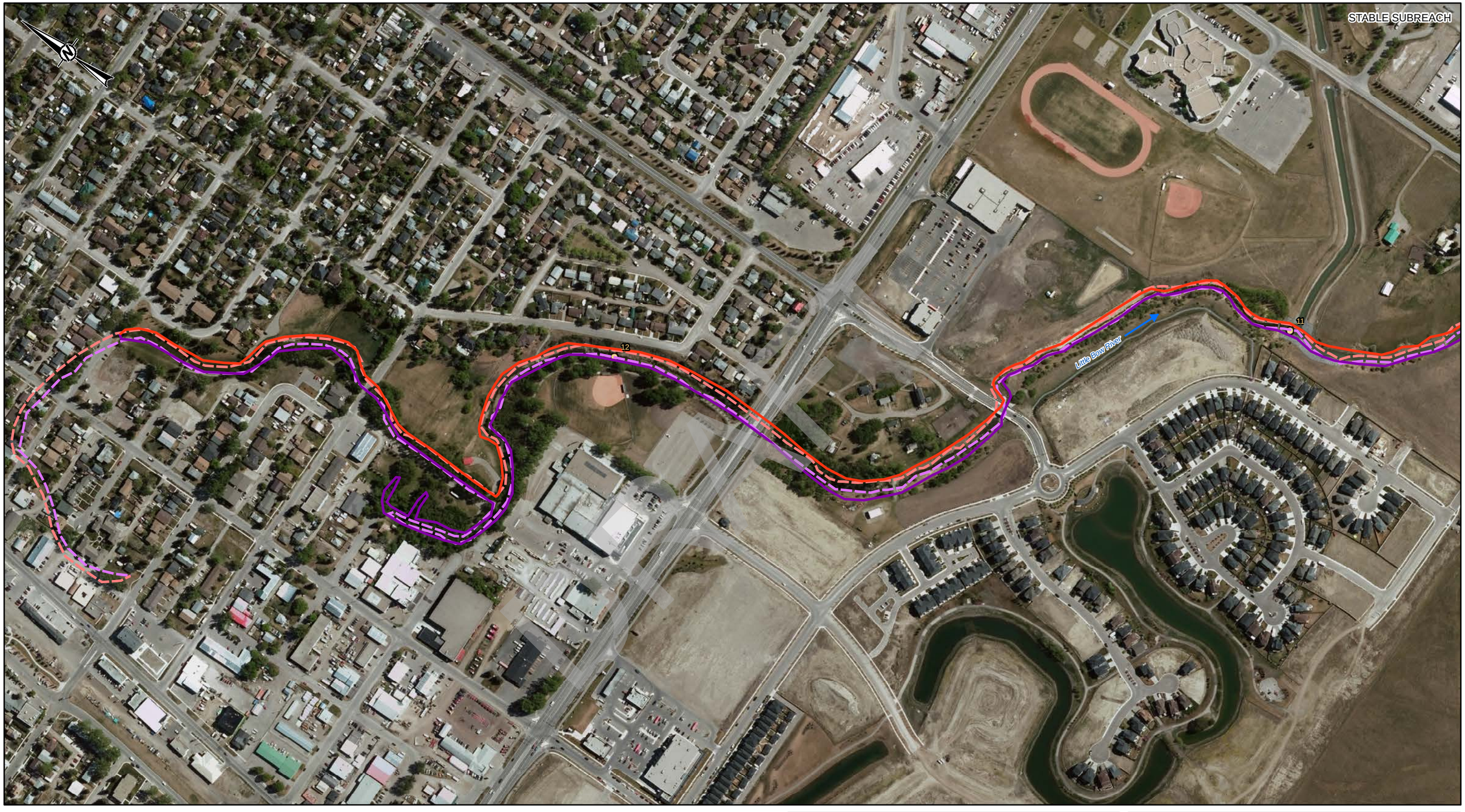

LEGEND

- RIVER STATION POST
- FLOW DIRECTION
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- RIGHT BANK HISTORICAL (1951)
- LEFT BANK (2016)
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- CHANNEL BAR (2016)
- CHANNEL BAR HISTORICAL (1951)
- FORESTED ISLAND (2016)
- FORESTED ISLAND HISTORICAL (1951)
- PROTECTED BANK (2016)

LEGEND KAY MAP

- STABLE SUBREACH
- UNSTABLE SUBREACH

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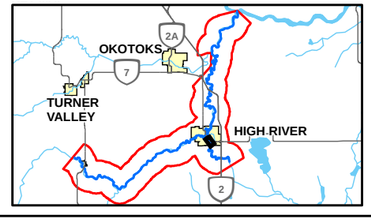
KEY MAP



PROJECT
HIGHWOOD RIVER HAZARD STUDY

PROJECT
LITTLE BOW UPPER REACH CHANNEL BANK COMPARISON - REPRESENTATIVE SUBREACHES

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PROJECT NO. 1536669 | CONTROL | REV. 0 | FIGURE **10**

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4.2 Cross-Section Comparison

Detailed qualitative and quantitative descriptions and figures for the cross-section comparison are presented in Appendix A. Table 6 provides a summary of estimated river geometry.

Table 6: Summary of Cross-section Observations

Reach	Average Bankfull Width (m)		Maximum Bankfull Depth (m)		Average Bankfull Depth (m)		Cross-Sectional Area (m^2)	
	1992/1950*	2016	1992	2016	1992	2016	1992	2016
1 - Sheep River to Bow River Confluence	105.6 (1950)	91.0	NA	3.3	NA	2.6	NA	219.5
2 - Tongue Creek to Sheep River	62.1 (1950)	55.5	3.0	3.5	2.4	2.9	119.2	149.4
3 - High River to Tongue Creek	65.0	52.0	3.7	4.2	2.9	3.3	153.6	157.0
4 - High River	102.3	65.9	3.7	3.6	2.1	2.2	166.8	130.5
5a – Km 64 to High River	51.7	61.7	2.3	2.7	1.4	1.7	67.5	97.5
5b - Pekisko Creek to Km 64	75.1 (1950)	78.1	NA	3.4	NA	2.5	NA	187.5
6 - Upstream Boundary of Study Area to Pekisko Creek	76.2 (1950)	67.6	NA	2.8	NA	2.2	NA	155.1
7 - Little Bow Upper Reach	15.4 (1950)	16.4	NA	1.5	NA	1.0	NA	16.4
8 - Little Bow Lower Reach	8.8 (1950)	13.3	NA	2.4	NA	1.2	NA	17.1

* - Maximum bankfull width derived from 1950-1951 data where stated.

The main quantitative observations indicate average bankfull width has decreased between 8 m and 36 m along Reaches 1 to 4 and 6 on Highwood River and on both Little Bow Reaches, suggesting a narrowing of the channel. This was confirmed by the observations made during the channel bank comparison. In most cases this narrowing of the channel occurred due to stabilization of side bars along the river, based on observations made during the channel bank comparison.

Average bankfull width has increased along Reaches 5a and 5b by between 3 m and 10 m, suggesting a widening of the river channel. The average bankfull depth has increased along Reaches 2 through 5a, suggesting a deepening of the river. Cross-sectional area has decreased along Reaches 2 and 4 and increased along Reaches 3 and 5a. Typically, changes observed were not statistically significant, at the p=0.05 level, with the exceptions of the changes to average bankfull width and average bankfull depth along Reach 2 and the average bankfull depth along Reach 5a. These changes were significant at the p = 0.05 level.

As mentioned in Section 0, cross-section data within Reach 2 were not available from the location of 0.5 km downstream of the Highway 2 Bridge Crossing to the Sheep River confluence. While the cross-section data for Reach 2 are taken to be representative for this reach of the river upstream of the Highway 2 Bridge Crossing it is possible that downstream of Highway 2 Bridge Crossing the cross-section data are not representative. In the absence of other data, it has been assumed that the cross-section data are a reasonable approximation for the downstream portion of the reach. .

Where possible, the lateral migration of the channels was documented during the cross-section comparison. Lateral migration along Reaches 2, 3 and 4 ranged from 5 m to 80 m, typically resulting in a narrowing of the channel. Lateral migration along Reach 5a ranged from 0 m to 80 m and typically resulted in the widening of the channel.

4.3 Thalweg Profile Comparison

A thalweg comparison was conducted for the 1992 and 2016 profiles. Figure 12 shows the comparison of the two thalwegs in terms of elevation and distance downstream. Due to the scale of Figure 12, detailed changes are difficult to interpret, so a difference plot was created to highlight measured changes in the two thalwegs. The difference plot is shown in Figure 13. The difference plots simplify the differences between the two thalwegs such that positive numbers are indicative of accretion or aggradation and negative numbers are indicative of erosion. Table 7 summarizes, by reach, the average slope and the net bed change calculated from the thalweg comparison.

According to Ritter et al. (1995), thalwegs exhibiting a concave-upward profile shape are typical of a stream reach in equilibrium. Figure 11 shows an example of a typical concave-upward thalweg for comparison. The plots for both the 1992 and 2016 thalwegs do not follow a monotonically decreasing concave-upward profile indicative of generally stable conditions. Inspection of the thalweg for each reach suggests that Reaches 1, 5a, 5b and 6 on Highwood River follow a general concave-upward trending profile with slopes typically decreasing in steepness from the upstream boundary to the river mouth. Reach 6 at the upstream boundary has a slope of 0.0045, while Reach 1 at the downstream boundary has a slope of 0.0025. Reaches 2 to 4 do not follow this trend, as shown in Figure 12. Reach 2 with a slope of 0.0019 has a slightly gentler slope than Reach 1, but steeper than Reach 3. Detailed inspection of the thalweg along Reach 3, shows a highly undulating river bed which trends downward at a very gentle slope of 0.0003. Reach 4, has a slope of 0.0015 and also has a highly undulating bed.

The observed deflection of the thalweg profile along these three reaches suggests the potential for a stream not in equilibrium and/or subject to instability from the community of High River downstream to the Sheep River confluence. The presence of a region of decreased slope from the Highway 2A Bridge (km 48.7; Reach 4) to the Highway 2 Bridge (km 30.7; Reach 2) suggests that this reach is prone to aggradation and channel instability due to the reduced capacity to transport sediment through the flatter slope section between the steeper upstream reaches to the steeper downstream reaches. This is evident in areas of net bed accretion as shown in Figure 13 from approximately km 32 to 34 and km 38 to 40.

The net bed change was calculated where historical thalweg data was available for the section of Reach 2 upstream of the Highway 2 Bridge crossing, and Reaches 3 through 5a. A reduction in bed elevation was observed on the upstream section of Reach 2 and Reaches 4 and 5a while a net bed increase was observed on Reach 3. The total net bed change along the four reaches was approximately a decrease of 1,057 m^3.

A thalweg comparison could not be conducted for Little Bow River, but the 2016 surveyed thalweg is shown in Figure 14. Little Bow River originates in the Town of High River and flows towards the south. Water in the river is redirected from Highwood River into Little Bow Canal which discharges into the main channel at approximately Km 11 (as shown in Figure 2e and Figure 10). The slopes for the upper (Reach 8) and lower (Reach 7) reaches are 0.0031 m/m and 0.0016 m/m, respectively. The undulating thalweg morphology with an approximately linear (consistent) slope within the study area (see Figure 14) suggests that this channel could be non-alluvial, where the river channel has not developed in sediments carried by the river itself, or a former outwash channel shape. If the latter then the channel slope and thalweg profile could be relict features of processes no longer operating in the modern environment.

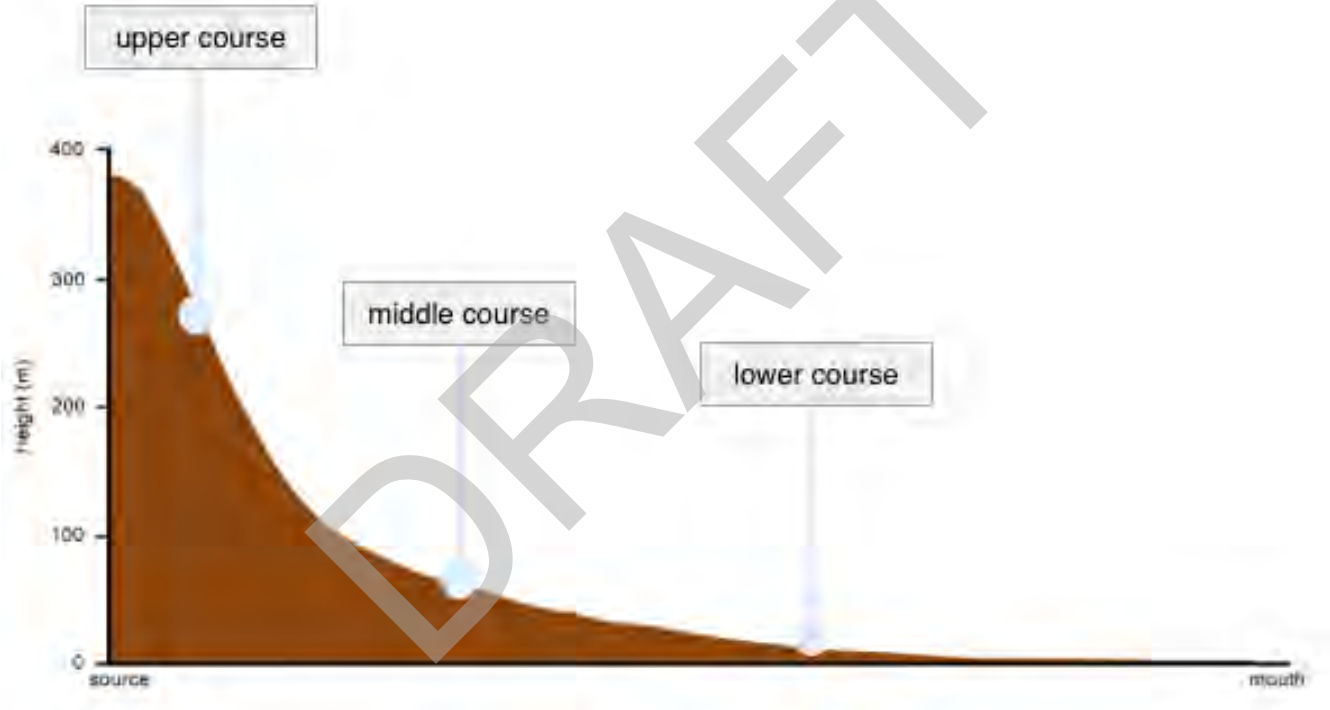

Figure 11: Graded River with a Typical Concave-upward Thalweg Profile

(Source: http://www.geography.learnontheinternet.co.uk/topics/longprofile.html)

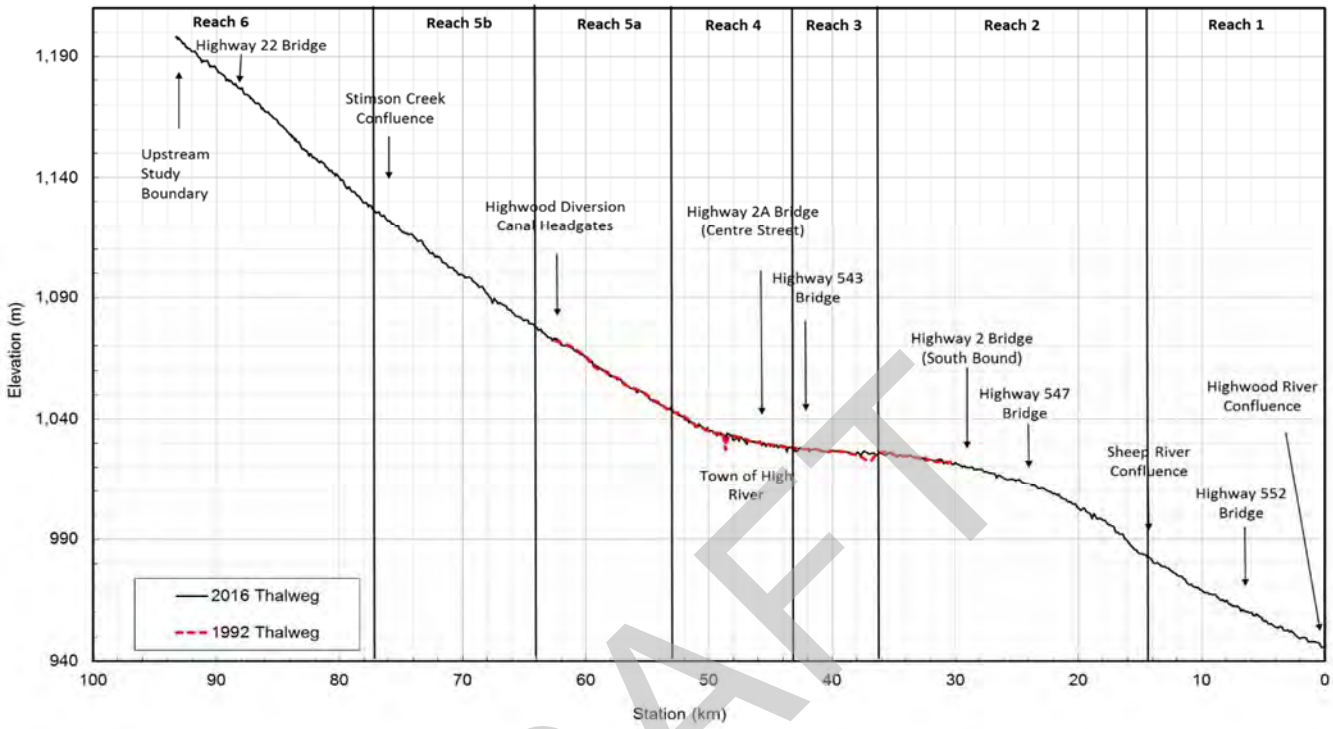

Figure 12: Highwood River Thalweg Comparison

Notes: (1) change in longitudinal profile from concave to convex at the boundary between Reach 2 and Reach 3 and back to concave at the boundary between Reach 1 and Reach 2.

Table 7: Summary of Net Bed Change from Thalweg Comparison (1992 vs 2016)

Reach	Marker Posts (km upstream)	Average Reach Slope (m/m)	Net Bed Change (m^3)
1 - Sheep River to Bow River Confluence	0 to 14.2	0.0025	NA
2 - Tongue Creek to Sheep River	14.2 to 36.1	0.0019	- 768
3 - High River to Tongue Creek	36.1 to 43.1	0.0003	2,216
4 - High River	43.1 to 53.2	0.0015	- 695
5a – Km 64 to High River	53.2 to 64.0	0.0031	- 1,809
5b – Pekisko Creek to Km 64	64.0 to 77.3	0.0038	NA
6 - Upstream Boundary of Study Area to Pekisko Creek	77.3 to 93.5	0.0045	NA
7 - Little Bow Lower Reach	0 to 11.0	0.0016	NA
8 - Little Bow Upper Reach	11 to 12.9	0.0030	NA
Total Net Bed Change for the Study Area			- 1,057

NA = historical thalweg or cross-section data not available so net bed change could not be calculated.

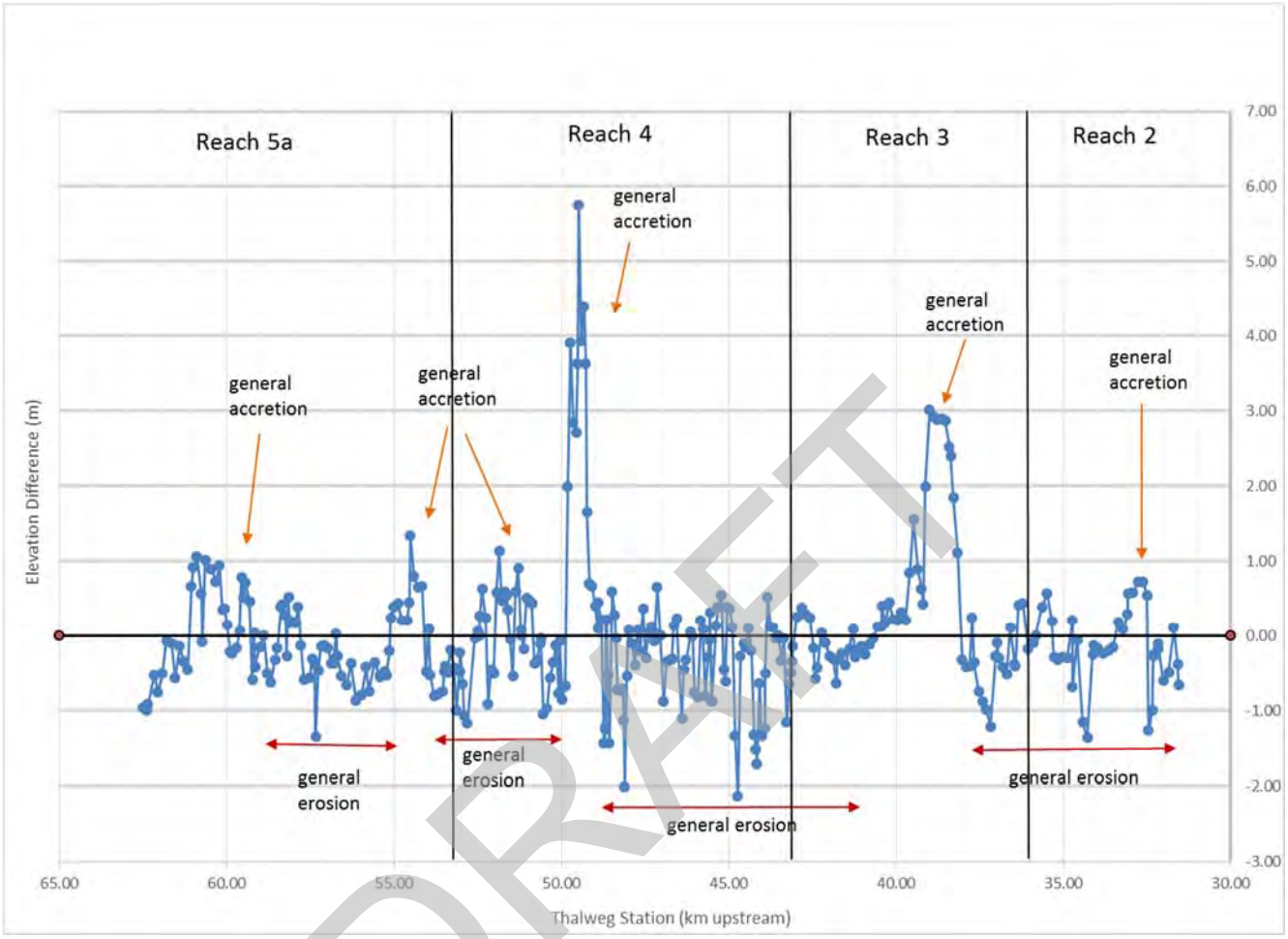

Figure 13: Highwood River Thalweg Elevation Difference, 1992 vs 2016

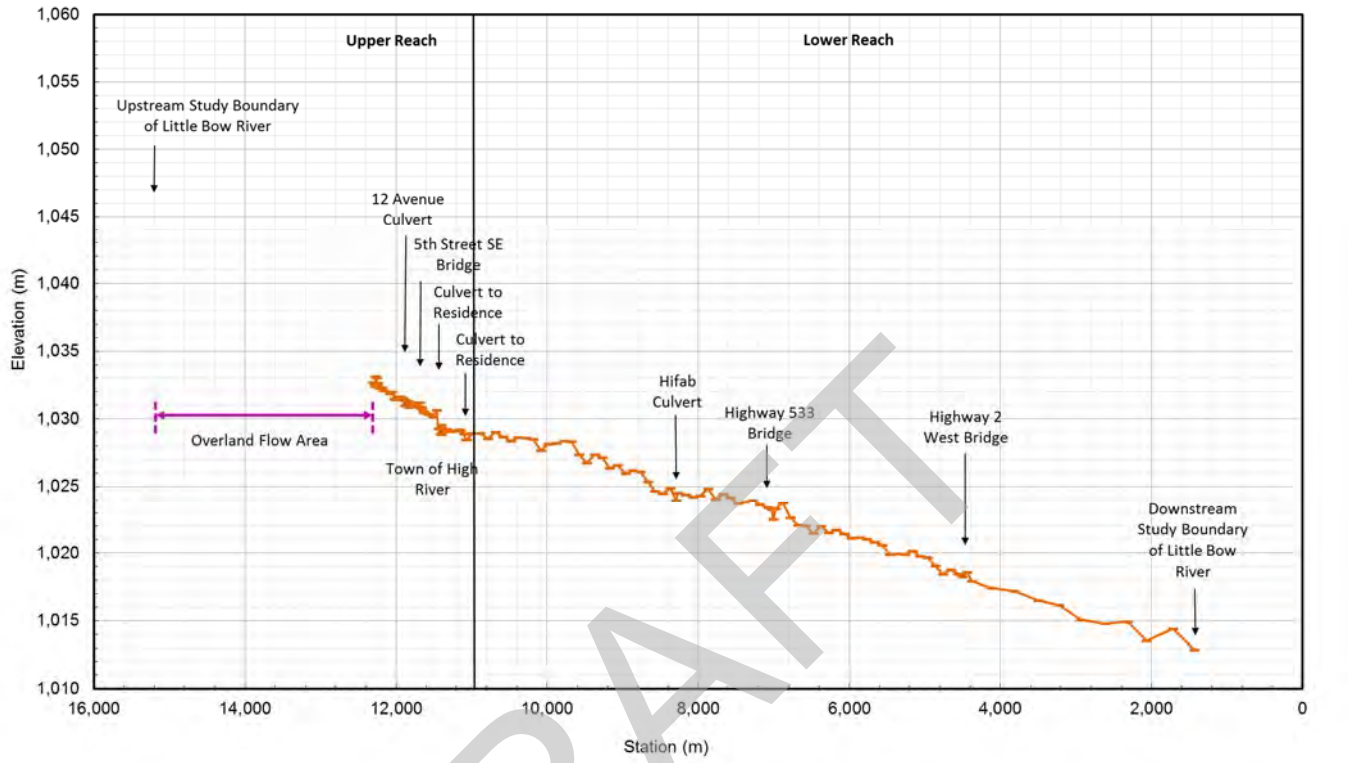

Figure 14: Little Bow River 2016 Thalweg

4.4 Rating Curve Comparison

The results of the rating curve comparison are shown in Figure 15 through Figure 17.

Highwood River below Little Bow Canal (Station 05BL004) is located along Reach 3 (i.e., High River to Tongue Creek within the Town of High River). The data for this station are shown in Figure 14. The change in the rating curve (see Figure 15) suggests narrowing or shoaling (accretion) of the channel because the same water surface elevation in 1987 and 2016 conveys less discharge in 2016. The loss of conveyance is likely due to a combination of narrowing, as observed in the cross-section comparison, possibly as a result of land use changes and limitation of channel adjustment by river training (based on air photo observations of the channel planform) and accretion, as shown by the thalweg comparison. The thalweg comparison along this reach identified a net bed accretion of 2,216 m^3.

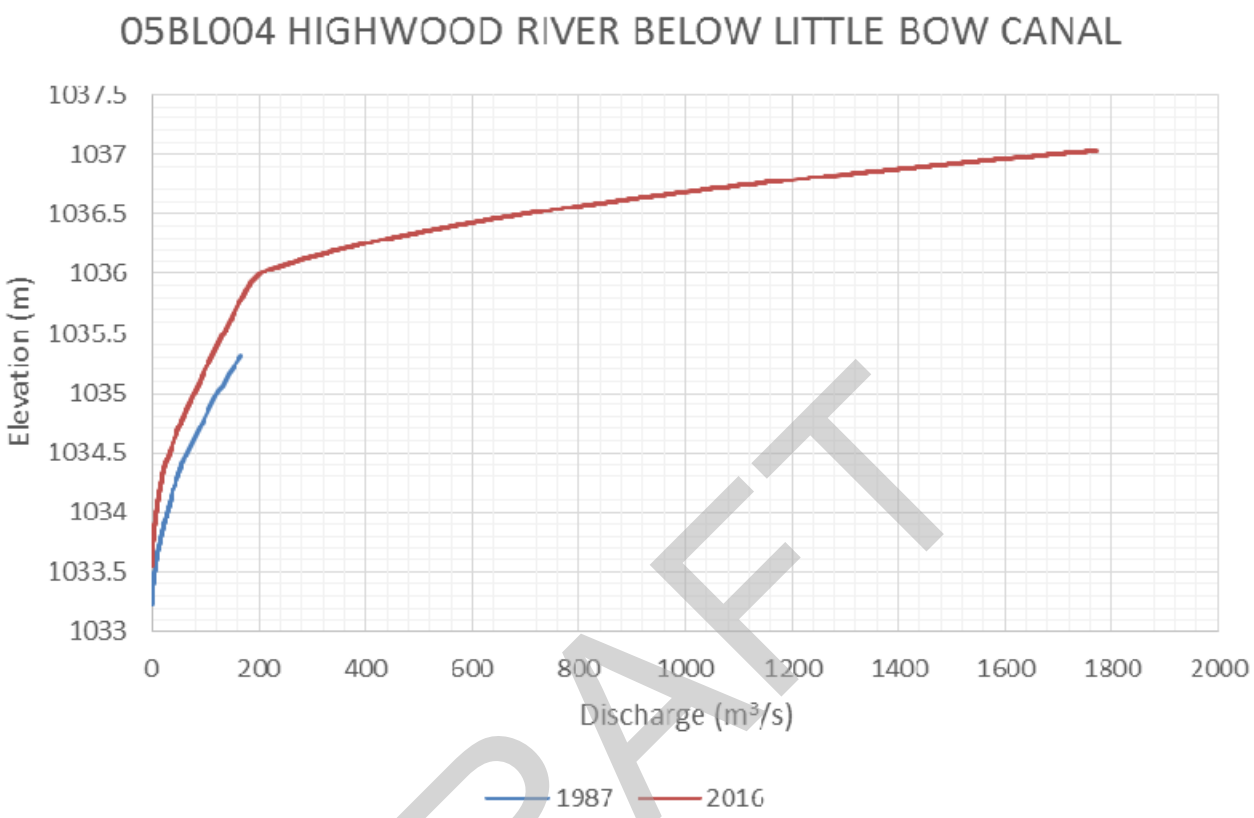

Figure 15: Highwood River below Little Bow Canal (Station 05BL004)

Figure 16 shows the rating curve comparison for the Highwood River station at the Bow River confluence (Station 05BL024). This station is located along Reach 1 which extends from Sheep River to the Bow River confluence. The change in curve suggests widening or deepening of the channel (erosion), because the same water surface elevation in 1970 and 2016 conveys more discharge in 2016 (e.g., the discharge was larger in 2016 for a given elevation). The lowering of the bed could be a function of channel engineering or excavation or the loss/winnowing of bed material related to potential down-cutting by Highwood River. The data from the channel bank comparison suggests that the lower portion of this reach is unstable but this could not be confirmed due to the absence of historical thalweg and cross-section data.

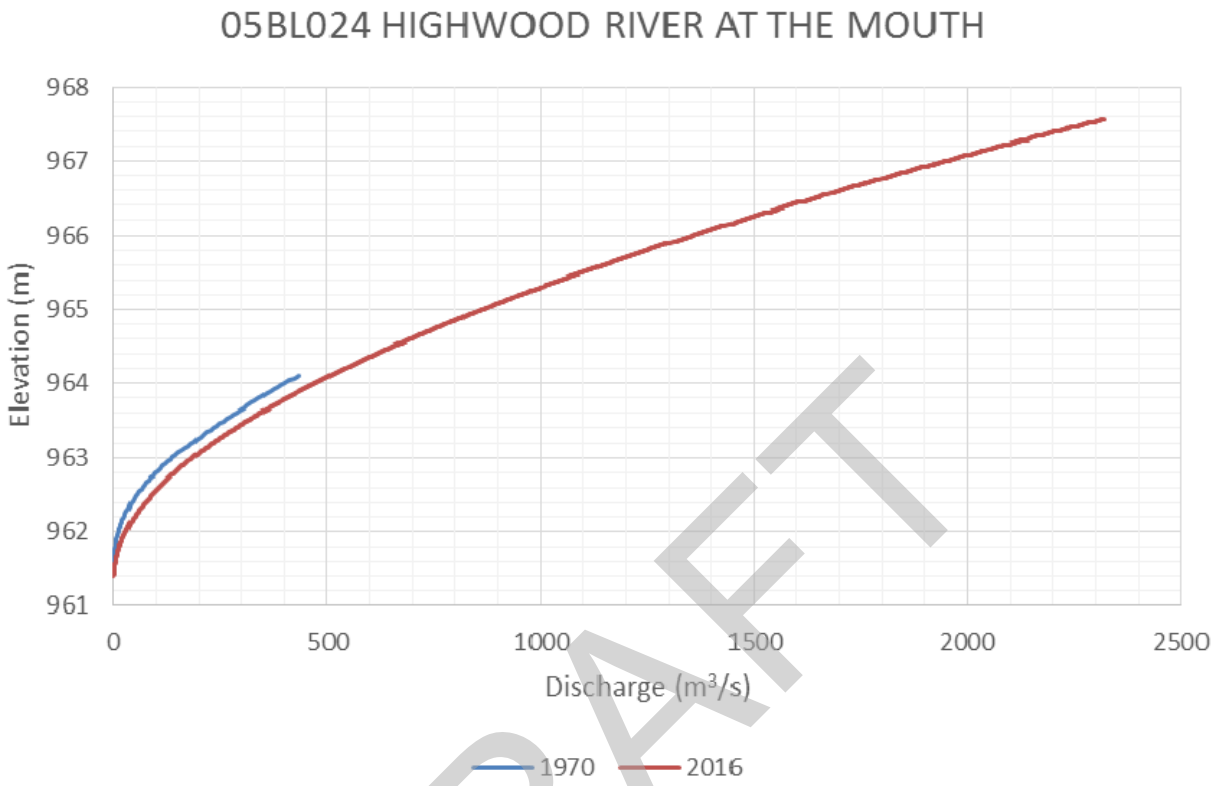

Figure 16: Highwood River near the Mouth (Station 05BL024)

Figure 16 shows the rating curve for Little Bow River (05BL015). The change in rating curve between 2003 and 2017 (see Figure 17) suggests a narrowing or shoaling (accretion) because the same water surface elevation in 2003 and 2017 conveys less discharge in 2017 (e.g., the discharge is larger in 2003 for a given elevation). The loss of conveyance is likely due to narrowing, possibly as a result of land use changes and limitation of channel adjustment by river training (based on air photo observations of the channel planform). This station is located within the Little Bow Canal. The canal is a man-made channel and was most recently reconstructed in 2003 prior to the collection of the 2003 rating curve data. Water and suspended sediments carried by Highwood River are likely diverted into the Canal potentially indicating that the observed changes in the rating curves between 2003 and 2017 may be due to the aggradation of the bed of the Canal due to sediment inputs from Highwood River.

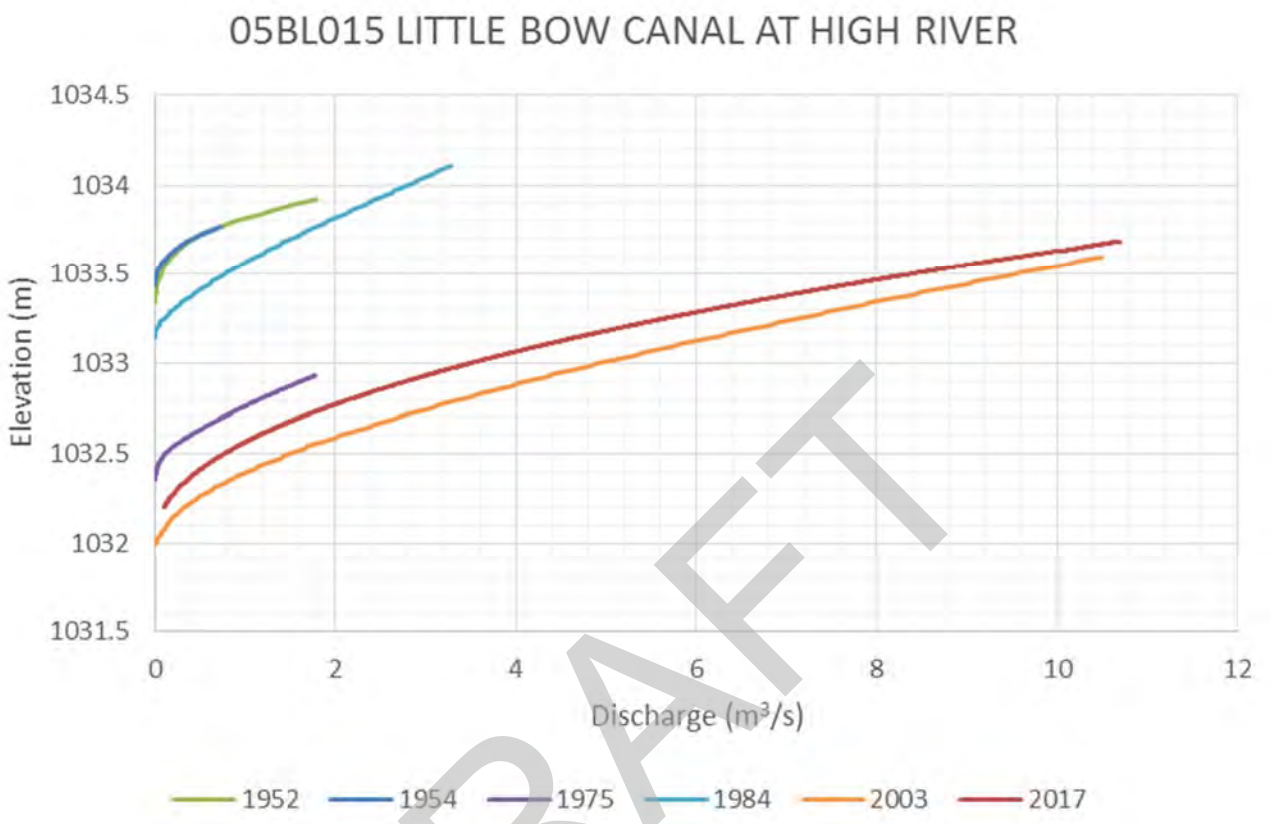

Figure 17: Little Bow Canal at High River (Station 05BL015)

Notes: (1) This gauge was moved in 1954, 1975, 1984 and 2003 which has caused vertical shifts in the datum.
(2) Curves for 1952 and 1954 are on the same datum. 2003 and 2017 curves are also on the same datum.

5.0 SUMMARY OF FINDINGS AND CONCLUSIONS

5.1 Highwood River

5.1.1 Reach 1

The most downstream reach of Highwood River, Reach 1, is categorized as a sinuous, single channel river reach confined within a larger incised channel (suspected glacial outwash channel).

Visual evidence in the form of an increase in the occurrence of point and side bars from the aerial imagery suggests that Sheep River is a major contributor of sediment to Highwood River. As such, Reach 1 which is downstream of the Sheep River confluence contains more sediment than Reach 2, appears to have more active bars. Significant lateral migration at the Bow River confluence and the presence of active bars and migrating forested islands suggests that the very lowest section of Reach 1 is unstable.

Due to the confined nature of the channel within this reach, limited lateral migration is occurring. While narrowing of the channel in this reach was observed in the cross-section data, the change is not statistically significant. Due to the confined nature of the channel and limited lateral migration, this reach is considered predominantly stable with the exception of the section immediately upstream of the Bow River confluence.

The surface water elevations associated with the 2013 flood event overtopped the channel banks along this reach. However, based on the morphological data reviewed, it appears that the capacity of the river to handle discharge has not changed over the extent of historical data reviewed.

5.1.2 Reach 2

Reach 2 of Highwood River is categorized as a sinuous, single channel river reach confined within a larger incised channel (suspected glacial outwash channel).

Evidence for narrowing and down-cutting of the channel observed in the cross-section data, is considered to be statistically significant. The narrowing of the channel over time is possibly a result of land use changes and limitation of channel adjustment by river training (based on air photo observations of the channel planform) or diversion of Highwood River flow into Little Bow River, therefore reducing the average discharge of Highwood River.

Evidence for down-cutting was observed within the section of Reach 2 upstream of the Highway 2 Bridge crossing in the form of a net bed change of -768 m^3 based on an analysis of the thalweg data. Changes to the channel geometry along Reach 2 may be the result of changes in the thalweg elevation occurring slightly upstream of this reach. The down-cutting along the upstream section of Reach 2 inferred by the overall lowering of the thalweg may be the result of the river attempting to increase the gradient along this reach which has a gentle slope along its upstream end and a steeper slope at the downstream end leading to a convex-upwards profile through the reach.

While the narrowing and down-cutting along Reach 2 are considered to be statistically significant, due to the confined nature of the channel and limited lateral migration, this reach is considered to be stable. The 2013 flood event did not overtop the channel banks along this reach.

5.1.3 Reach 3

Reach 3 of Highwood River is characterized as a sinuous and single channel river reach. It differentiates from Reaches 1 and 2 in that it is not contained within the larger confined channel and has a very shallow slope (0.0003) with a net bed accretion occurring between km 38 and km 40.

The net bed change along this reach is estimated to be 2,216 m^3 based on an analysis of the thalweg data. However, in the cross-section comparison, only one of the five cross-sections along Reach 3 showed a shallowing of the bed (Cross-section 14, Appendix A). The other four cross-sections showed a deepening of the bed (Cross-sections 12, 16, 18 and 21, Appendix A). The 1992 thalweg shows a small, localized basin in this area and therefore some of the net bed accretion may be attributed to its infilling. The longitudinal shape of the thalweg along this reach suggests instability, due to its concave-upwards profile.

The observed accretion suggests that the river is attempting to increase the slope along this reach to return to a more equilibrium profile and to return the longitudinal shape of the thalweg towards a concave-upward profile that can maintain competent sediment transport along the river. This sediment accretion is likely to be ongoing and would typically result in increased flood hazard with time through Reach 3 as the riverbed aggrades as a whole to increase local streambed gradient.

5.1.4 Reach 4

Reach 4 of Highwood River is characterized as a sinuous, tortuous sometimes single channel and sometimes multi-thread channel in a broad floodplain with actively migrating side, point and mid-channel bars. Relict oxbow channels can be seen in the aerial photography suggesting a highly mobile channel. Reach 4 has a slope of 0.0011, which is more shallowly sloped than Reaches 1, 2, 5a, 5b and 6 but is steeper than Reach 3 (see Figure 12).

This reach has an estimated net bed loss of -695 m^3 based on an analysis of the thalweg data. As a highly mobile channel with active bars, Reach 4 is considered to be unstable. However, as changes to channel geometry over time are not statistically significant, it is not suspected that the capacity of the river to handle discharge has changed.

5.1.5 Reach 5a

Reach 5a of Highwood River is similar to Reach 4 and is characterized as a sinuous, tortuous sometimes single channel and sometimes multi-thread channel in a broad floodplain with actively migrating side, point and mid-channel bars. As such, it may be considered an anastomosing reach due to its forested islands, multi-channeled sections and historical indications of avulsion.

Reach 5a has a slope of 0.0031, which is steeper that the slope of Reaches 1,2,3 and 4, and shallower than Reaches 5b and 6 (see Figure 12). This reach has an estimated net bed loss of -1,809 m^3 based on analysis of the thalweg data. Changes to the average bankfull depth along Reach 5a are considered statistically significant.

As a highly mobile channel with active bars, Reach 5a is considered to be unstable. However, as the channel has undergone a statistically significant deepening with a negative net bed change, it is estimated that the capacity of the river to handle discharge has increased and therefore improved the ability of the river to convey flood discharge.

5.1.6 Reaches 5b and 6

The upper reaches of Highwood River (i.e., Reaches 5b and 6) are characterized as single channel reaches with intermittent braiding within a deeply incised and confined larger channel. They are both categorized as having low sinuosity (sinuosity ≤ 1.3) and limited lateral migration was observed. Some stabilization of side and point bars was observed. Based on these observations, Reaches 5b and 6 are considered to be stable.

The water surface elevations associated with the 2013 flood event did not overtop the channel banks along these reaches.

5.2 Little Bow River

The lower and upper reaches of Little Bow River (i.e., Reaches 7 and 8) are characterized as single channel reaches.

Reach 8, the upper reach, is confined due to the presence of river training and diking along its full length and has a low sinuosity (sinuosity <1.3). No in-channel bars are present along this reach suggesting little to no sediment transport. This reach does not appear to have any obvious surface headwater sources, excluding the constructed diversion canal at the Town of High River.

The lower reach, Reach 7, is a partially confined and sinuous reach in a larger, more deeply incised valley suggestive of a larger river. Some mid-channel, point and side bars are present but do not appear to be active in terms of downstream migration and many historical side and point bars have stabilized into channel banks.

The thalweg for both the upper and lower reaches varies with several increases in elevation visible along its length. Based on the varying thalweg, lack of sediment transport and evidence of limited flow, Little Bow River, is estimated to be either a non-alluvial channel or confined within a geologically historical river valley (e.g., meltwater channel) and therefore the present undulating thalweg may be a relict feature.

Based on these observations, the Little Bow River is considered to be stable along the full length within the study area.

Table 8: Summary of Qualitative Reach Characteristics

Reach	Current Width to Depth Ratio	Reach Slope (m/m)	Sinuosity (thalweg length / straight valley length)	Summary of observations
1 - Sheep River to Bow River Confluence	40	0.0025	1.4	■ Single channel ■ Sinuous/meandering ■ Limited lateral migration except at the river mouth/Bow River confluence ■ Presence of side, point and forested bars ■ Incised, confined ■ Narrowing of channel
2 - Tongue Creek to Sheep River	20	0.0019	1.9	■ Single channel ■ Sinuous/meandering ■ Small side bars ■ Incised, confined ■ Stabilization of forested islands and side bars ■ Narrowing of channel ■ Deepening of channel ■ Increase in cross-sectional area ■ Thalweg shape suggests instability ■ Net bed change = -768 m^3
3 - High River to Tongue Creek	16	0.0003	1.6	■ Single channel ■ Sinuous/meandering ■ Limited lateral migration ■ Small side bars ■ Stabilization of forested islands and side bars ■ Incised, confined ■ Narrowing of channel ■ Deepening of channel ■ Thalweg shape suggests instability ■ Net bed change = +2,216 m^3
4 - High River	33	0.0011	2.1	■ Single and multi-thread channel ■ Significant lateral migration ■ Highly meandering ■ Relict oxbows ■ Numerous migrating side bars ■ Non-confined ■ Large forested islands ■ Numerous side, point and mid-channel bars ■ Decrease in cross-sectional area ■ Insignificant change in channel depth (±0.1 m) ■ Thalweg shape suggests instability ■ Net bed change = -695 m^3
5a – Km 64 to High River	38	0.0031	1.5	■ Single and multi-thread channel ■ Tortuous, braided ■ Non-confined ■ Large forested islands ■ Numerous side, point and mid-channel bars ■ Avulsion scars ■ Widening of the channel ■ Increase in cross-sectional area ■ Deepening of channel ■ Thalweg shape suggests instability ■ Net bed change = -1,809 m^3
5b – Pekisko Creek to Km 64	36	0.0038	1.1	■ Single channel ■ Limited lateral migration ■ Side, point and mid-channel bars ■ Stabilization of forested islands and side bars ■ Incised, confined ■ Narrowing of channel
6 - Upstream Boundary of Study Area to Pekisko Creek	32	0.0045	1.3	■ Single channel ■ Limited lateral migration ■ Side, point and mid-channel bars ■ Stabilization of forested islands and side bars ■ Incised, confined
7 - Little Bow Lower Reach	12	0.0016	2.1	■ Single channel ■ Limited lateral migration ■ Side, point and mid-channel bars ■ Stabilization of side bars ■ Slightly incised, confined ■ Controlled flow ■ Narrowing of channel, cross-section comparison resulted in insignificant change in width
8 - Little Bow Upper Reach	17	0.0030	1.3	■ Single channel ■ Low sinuosity ■ Limited lateral migration ■ No bars ■ Channelized/diked ■ No flow ■ Widening of channel

Report Signature Page

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APPENDIX A

Cross-Section Comparisons

Reach	Cross-section ID	Km Marker	Cross-sectional Area (m^2)		Maximum Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2015	1992	2015	1992	2015	1992	2015	
2 - Tongue Creek to Sheep River	1	30.4	90	66	65	55	3.1	3.6	2.0	2.2	- left-handedness - skewed to left - single channel - approx. 15 m and 35 m lateral migration of left bank and right banks to the left, respectively - narrowing of channel - deepening of channel by approx. 0.5 m in depth
	3	30.9	150	120	70	45	3.0	4.5	2.5	3.0	- right-handedness - skewed to right - single channel - approx. 5 m and 30 m lateral migration of right bank and left banks to the right, respectively - narrowing of channel - deepening of channel by approx. 1.5 m in depth
	5.2	32.2	110	100	70	60	3.3	3.5	2.4	2.5	- right-handedness - skewed to right - single channel - approx. 10 m lateral migration of both right bank and left banks to the right - slight narrowing of channel - deepening of channel by approx. 0.2 m in depth
	7	33.1	100	120	60	50	3.0	3.2	2.5	2.7	- left-handedness - slightly skewed to left - single channel

Reach	Cross-section ID	Km Marker	Cross-sectional Area (m^2)		Maximum Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2015	1992	2015	1992	2015	1992	2015	
											- approx. 15 m lateral migration of right bank to the left - narrowing of channel - deepening of channel by approx. 0.2 m in depth
	8	34.1	175	140	70	55	3.7	3.8	3.5	3.5	- right-handedness - slightly skewed to right - single channel - approx. 10 m lateral migration of right and left banks to the right - deepening of channel by approx. 0.1 m in depth
	10	35.3	90	115	70	75	1.7	1.9	1.5	1.6	- right-handedness - slightly skewed to right - single channel - approx. 10 m and 15 m lateral migration of right and left banks, respectively to the right - widening of the channel - deepening of channel by approx. 0.2 m in depth
3 - High River to Tongue Creek	12	36.4	160	140	50	45	3.3	4.7	3.5	3.5	- centred thalweg - slightly skewed to left - single channel - approx. 5 m lateral migration of left bank to the right - slight narrowing of the channel - deepening of channel by 0.5 m
	14	37.7	175	160	80	50	5.5	5.2	3.5	4	- left-handedness - slightly skewed to left, current channel more uniform

Reach	Cross-section ID	Km Marker	Cross-sectional Area (m^2)		Maximum Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2015	1992	2015	1992	2015	1992	2015	
											- single channel - approx. 5 m lateral migration of left and right banks to the left - narrowing of the channel near the bankfull water level, vertical aggradation of right hand side bar - shallowing of channel by 0.3 m
	16	39.2	175	150	85	55	3.5	3.6	2.5	2.7	- right-handedness - skewed to right - single channel - approx. 45 m and 15 m lateral migration of left and right banks, respectively to the right - narrowing of the channel - slight deepening of channel by approx. 0.1 m in depth
	18	40.4	168	165	70	60	3.8	4.1	2.8	3.0	- left-handedness - skewed to left - single channel - vertical aggradation of right hand point bar - deepening of channel by 0.3 m
	21	42.4	90	170	40	50	2.5	3.3	2.0	3.4	- left-handedness - skewed to left - single channel - vertical aggradation of right hand channel side bar - elevation of channel bed is relatively stable but elevation of bankfull water level has increased.
4 - High River	22	43.1	175	200	80	75	4.0	5.2	3.5	4.0	- right-handedness - skewed to right

Reach	Cross-section ID	Km Marker	Cross-sectional Area (m^2)		Maximum Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2015	1992	2015	1992	2015	1992	2015	
											- single channel - cross-section under bridge, changes to topography suspected to be anthropogenically controlled. - deepening of channel by approx. 1.2 m in depth
	24	44.2	110	100	55	40	3.6	3.0	3.1	2.6	- right-handedness - skewed to right - single channel - approx. 15 m lateral migration of left and right banks to the right - shallowing of channel by approx. 0.6 m in depth
	25	45.5	160	80	140	60	3.5	3.9	2.0	2.0	- channel changed from right-handed to left-handed - skewed to left - single channel - approx. 40 m lateral migration of left and right banks toward the centre of the channel - narrowing of channel by approximately 80 m - deepening of channel by approx. 0.4 m in depth
	27	47.2	180	105	90	40	3.0	3.7	2.0	2.6	- left-handedness - skewed to left - single channel - vertical and lateral (50 m to left) aggradation of right hand point bar - elevation of channel bed is relatively stable but elevation of bankfull water level has increased.

Reach	Cross-section ID	Km Marker	Cross-sectional Area (m^2)		Maximum Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2015	1992	2015	1992	2015	1992	2015	
											- narrowing of channel by approximately 50 m - deepening of channel by approx. 0.7 m in depth
	28	48.4	110	90	40	60	2.5	1.9	1.8	1.5	- channel changed from left-handed to right-handed - fairly uniform geometry - single channel - approx. 20 m lateral migration (widening) of right bank toward the right - shallowing of channel by approx. 0.6’ m in depth
	29	48.7	215	150	50	50	8.5	6.0	4.0	3.0	- right-handedness - skewed to right - single channel - cross-section under bridge, changes to topography suspected to be anthropogenically controlled. - approx. 10 m lateral migration of left and right banks to the right - shallowing of channel by approx. 2.5 m in depth
	30	48.9	150	160	100	80	2.7	3.7	1.5	2.0	- main channel between 900 and 1000 m along profile. - neighbouring floodplain highly developed - left-handedness - skewed to left - single channel - approx. 20 m lateral migration (narrowing) of left bank toward the right

Reach	Cross-section ID	Km Marker	Cross-sectional Area (m^2)		Maximum Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2015	1992	2015	1992	2015	1992	2015	
											- deepening of channel by approx. 1.0 m in depth
	32	49.5	210	140	140	80	3.6	3.7	1.5	2.0	- right-handedness - skewed to right - single channel - approx. 60 m lateral migration (narrowing) of left bank toward the right
	34	50.6	325	220	300	120	3.3	2.8	1.3	1.8	- right-handedness - skewed to right - single channel - accretion of large point bar within the channel has reduced cross-sectional area
	36	51.6	90	100	70	60	2.9	4.0	1.5	2.0	- left-handedness - skewed to left - single channel - approx. 5 m lateral migration (narrowing) of right bank toward the left - deepening of channel by approx. 1.1 m in depth - left bank of channel confined due to the bank protection
	38	53.0	110	90	60	60	2.7	2.0	1.3	1.1	- right-handedness - skewed to right - multi-channel - lateral migration of the channel approx. 20 m to the left - shallowing of channel by approx. 0.8 m in depth
	40	54.0	75	60	70	40	2.4	3.0	1.5	2.0	- left-handedness - skewed to left

Reach	Cross-section ID	Km Marker	Cross-sectional Area (m^2)		Maximum Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2015	1992	2015	1992	2015	1992	2015	
5 - Pekiski Creek to High River											- single channel - approx. 50 m lateral migration of mid-channel bar toward the left, becoming side bar - narrowing of main channel 30 m - deepening of channel by approx. 0.7 m in depth
	42	55.4	80	95	90	80	1.4	2.2	1.0	1.2	- left-handedness - skewed to left - single channel - approx. 10 m lateral migration (narrowing) of channel towards the left - slight deepening of channel by approx. 0.2 m in depth - 0.5 m vertical aggradation of right channel side bar and 0.8 m degradation of left channel side bar
	44	57.4	110	160	50	90	2.1	2.3	1.5	2.0	- left-handedness to right-handedness - skewed to left - multi-channel - approx. 40 m lateral migration (widening) of left bank towards the left - slight deepening of the channel by approx.. 0.4 m.
	47	59.2	40	90	50	65	3.8	2.9	1.2	1.5	- left-handedness to right-handedness - skewed to right - single channel - approx. 15 m lateral migration (widening) of right bank towards the right - shallowing of the channel by approx.. 0.8 m.

Reach	Cross-section ID	Km Marker	Cross-sectional Area (m^2)		Maximum Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2015	1992	2015	1992	2015	1992	2015	
	50	60.7	60	110	20	55	1.8	3.3	1.5	1.8	- left-handedness - skewed to left - multi-channel - approx. 80 m lateral migration of channel toward the left - widening of main channel by 35 m - deepening of channel by approx. 0.3 m in depth
	52	62.5	40	70	30	40	2.0	2.6	1.6	1.7	- right-handedness - skewed to left - multi-channel - approx. 80 m lateral migration of channel toward the left - widening of main channel by 10 m - 1 – 2 m aggradation on channel side bar

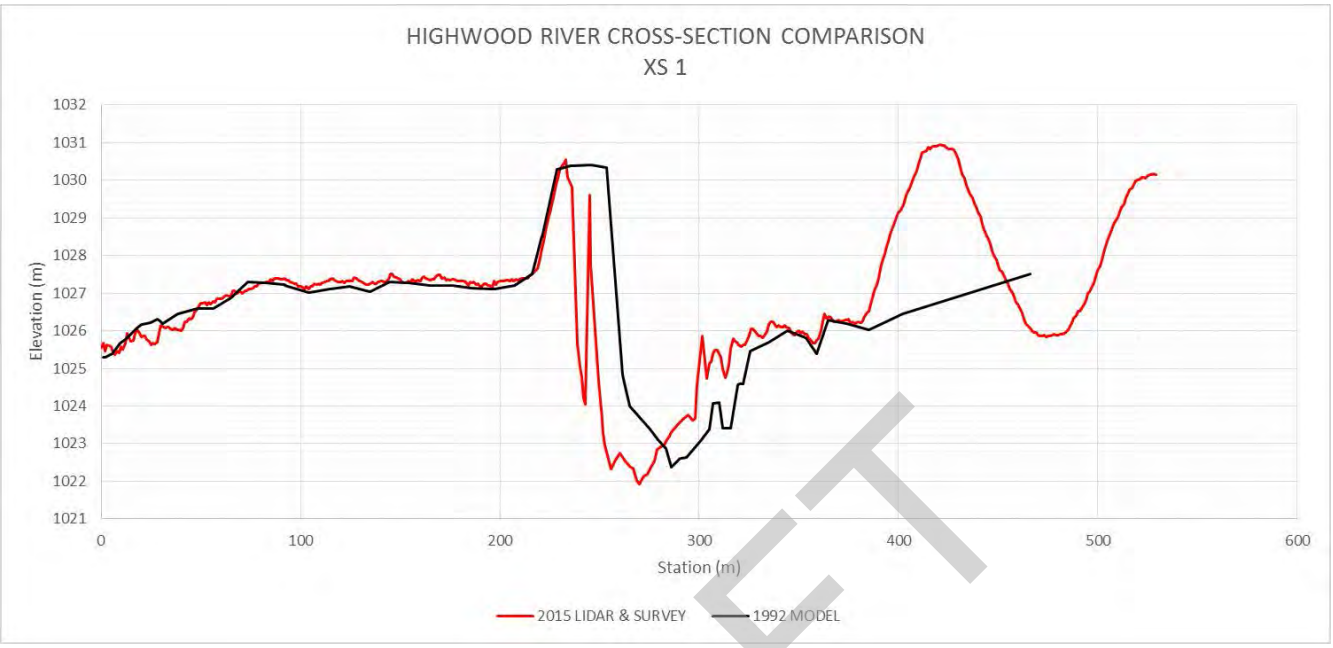


Figure A1: Highwood River Cross-Section 1 Comparison: 1992 Model and 2015 LiDAR and Survey

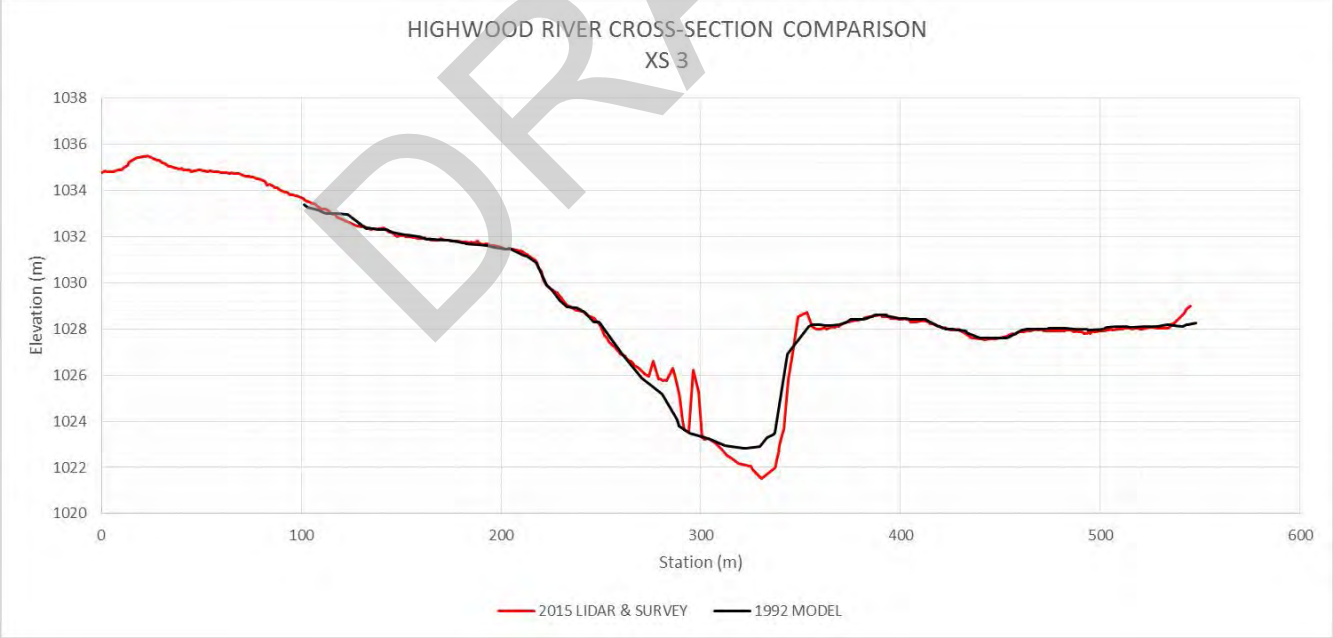


Figure A2: Highwood River Cross-Section 3 Comparison: 1992 Model and 2015 LiDAR and Survey

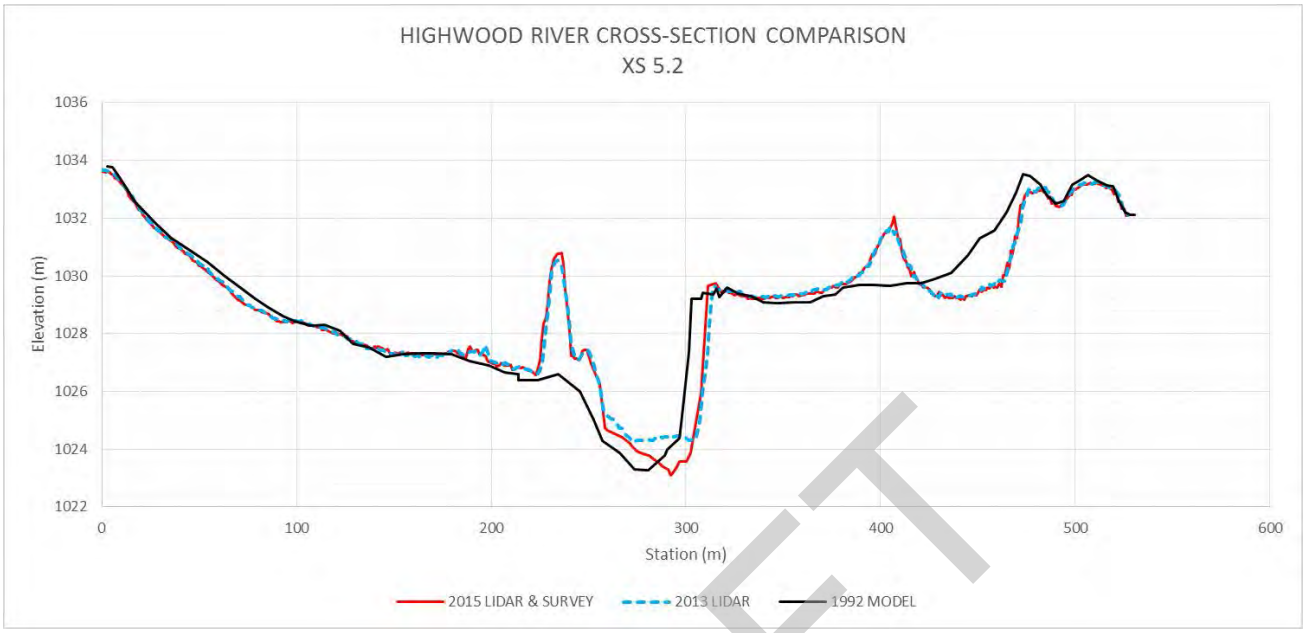


Figure A3: Highwood River Cross-Section 5 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey

Figure A4: Highwood River Cross-Section 7 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey

Figure A5: Highwood River Cross-Section 8 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey

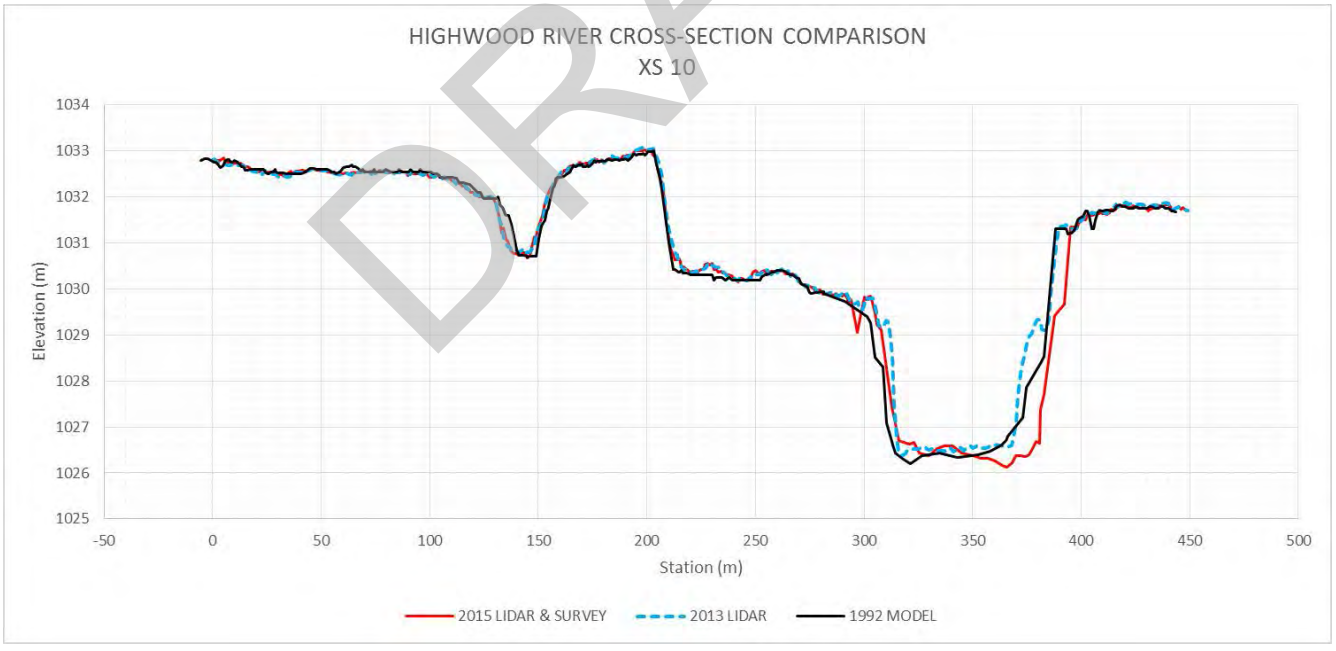


Figure A6: Highwood River Cross-Section 10 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

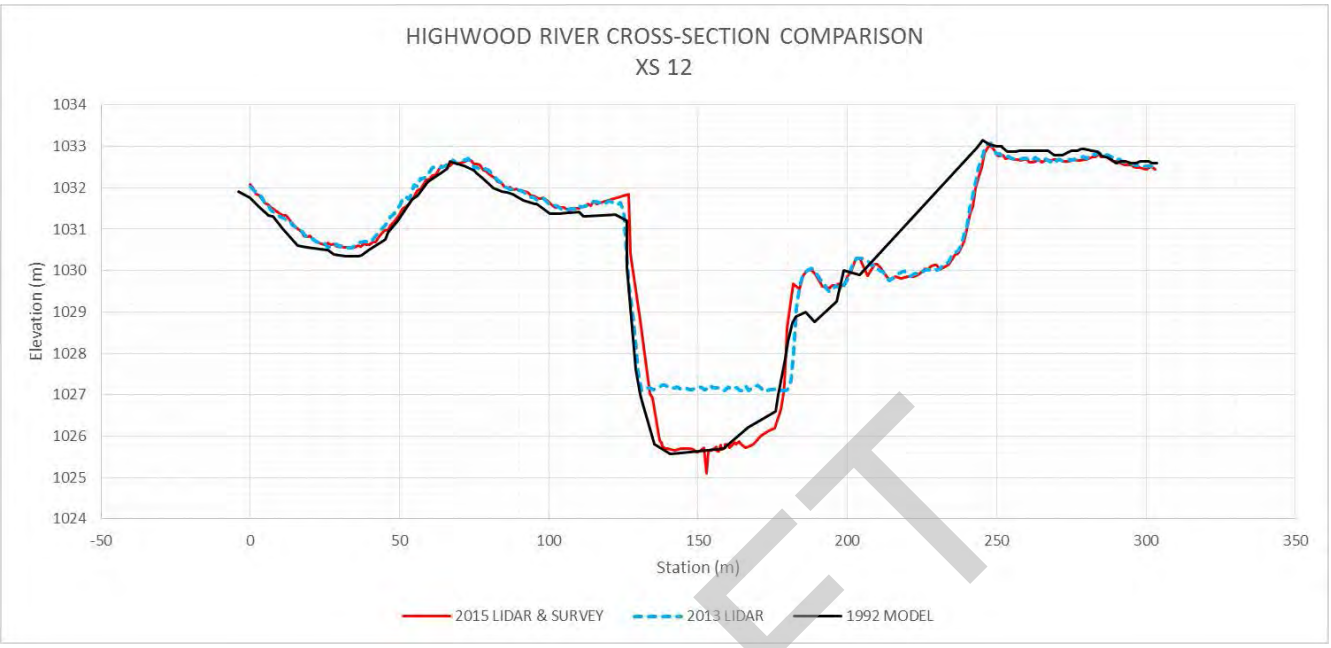


Figure A7: Highwood River Cross-Section 12 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey

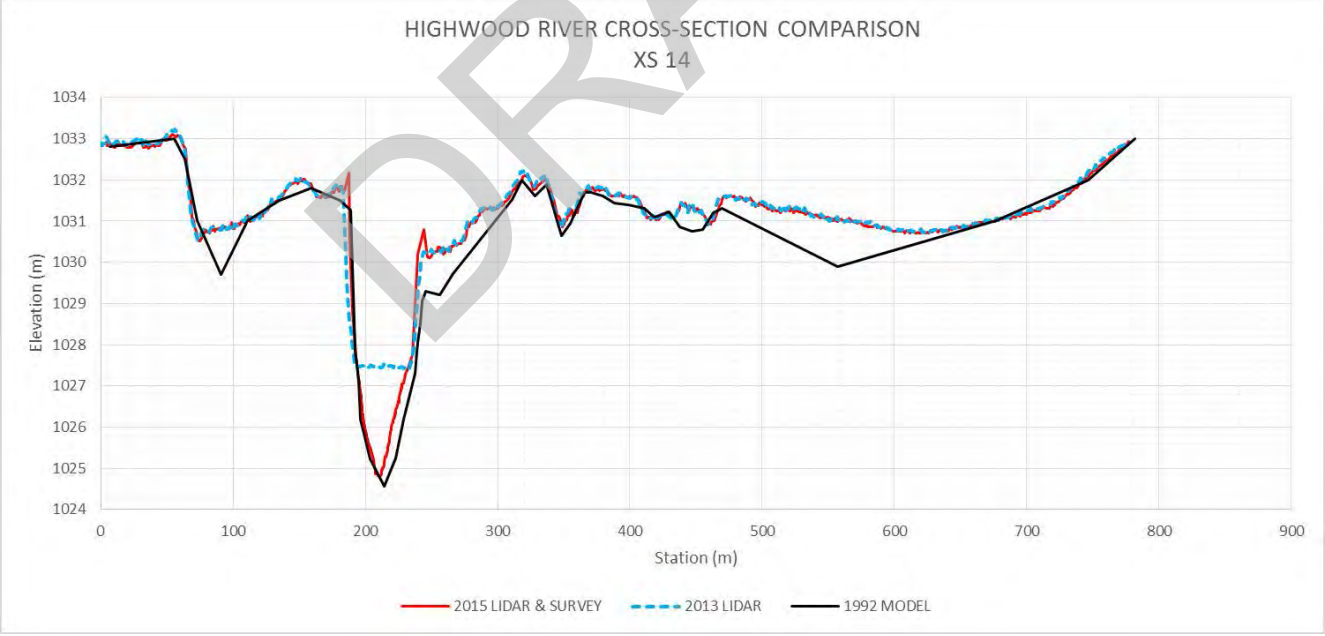


Figure A8: Highwood River Cross-Section 14 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

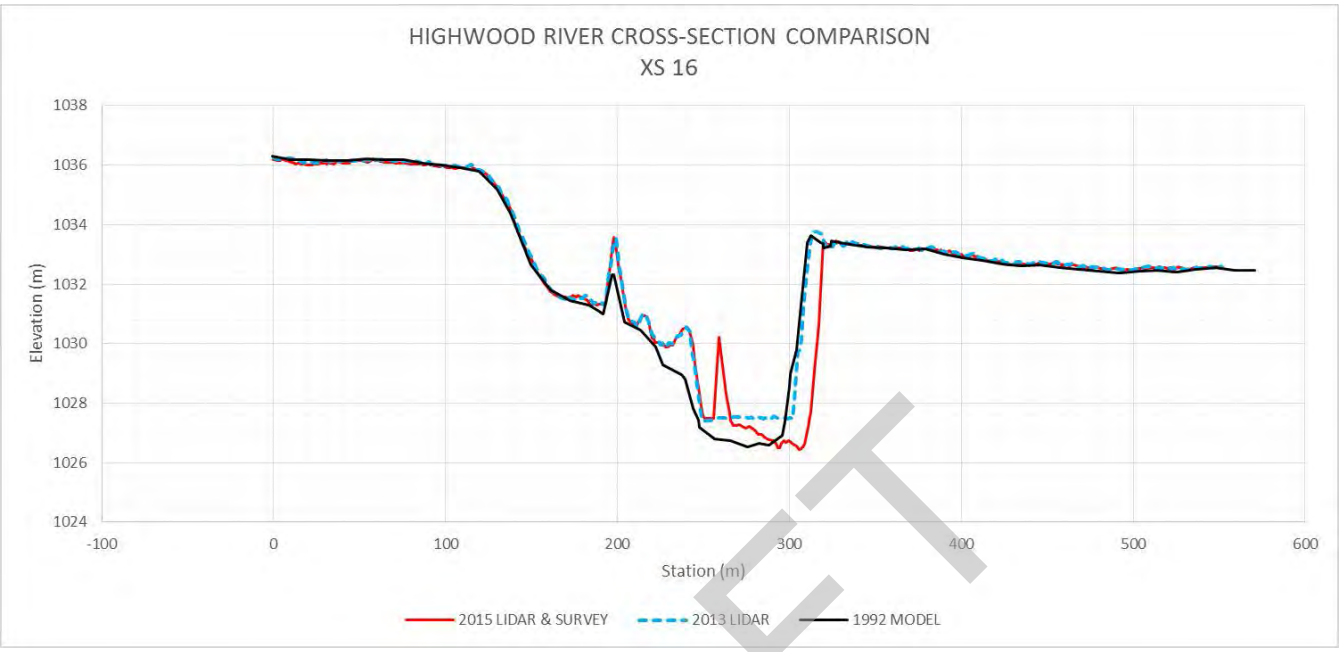


Figure A9: Highwood River Cross-Section 16 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

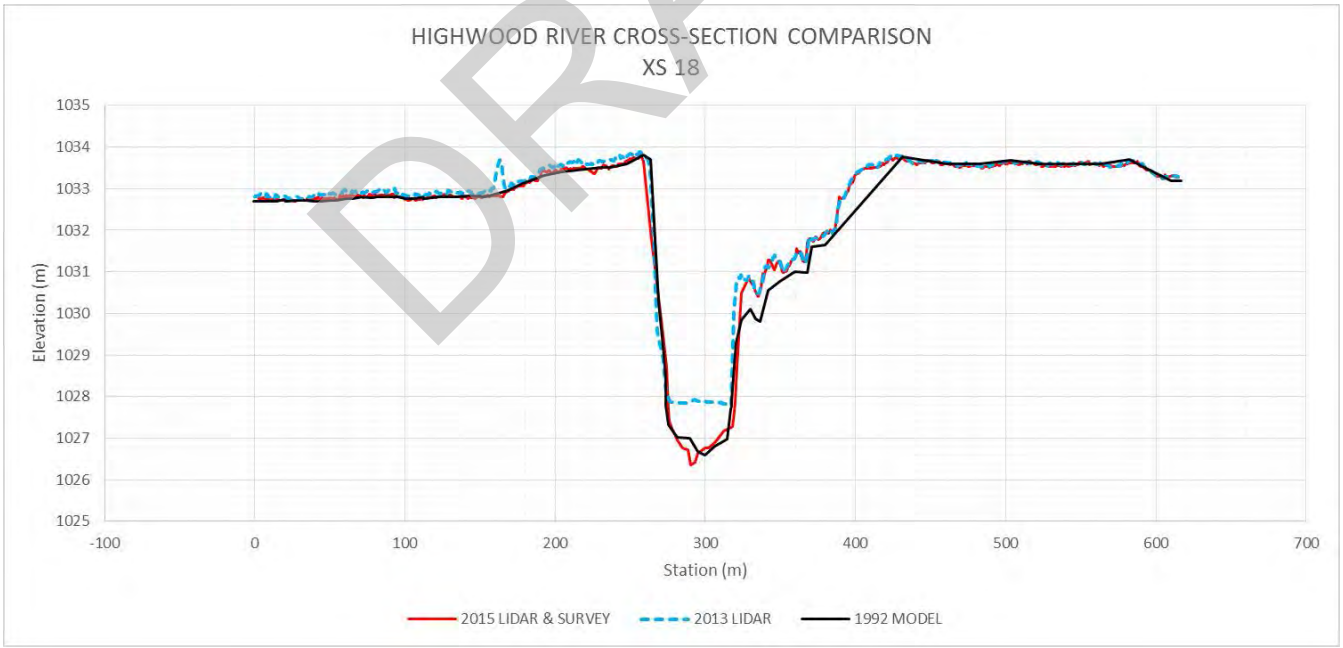


Figure A10: Highwood River Cross-Section 18 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

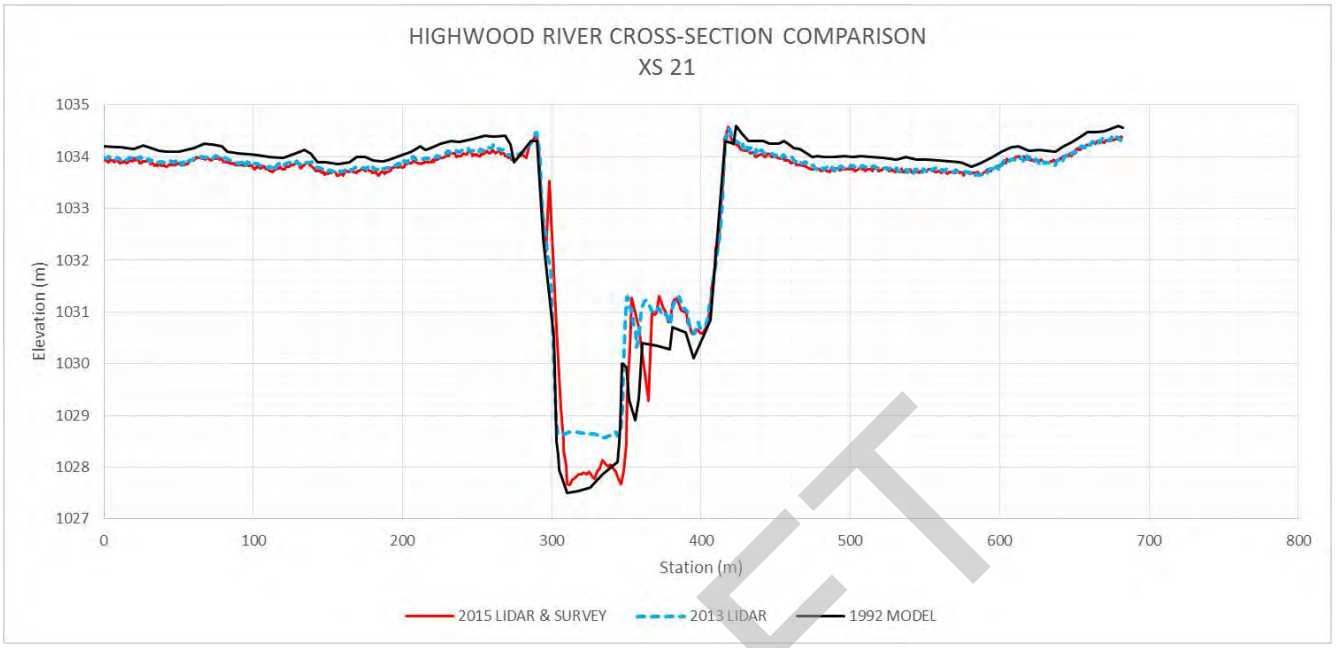


Figure A11: Highwood River Cross-Section 21 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey

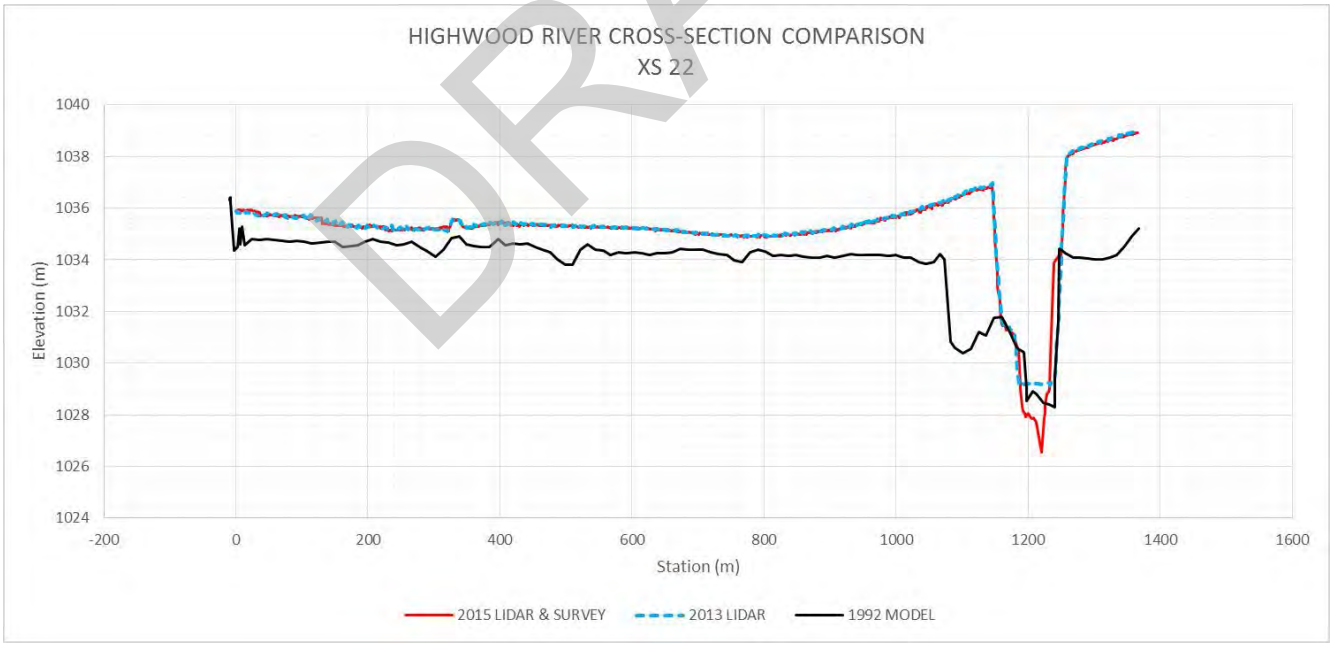


Figure A12: Highwood River Cross-Section 22 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

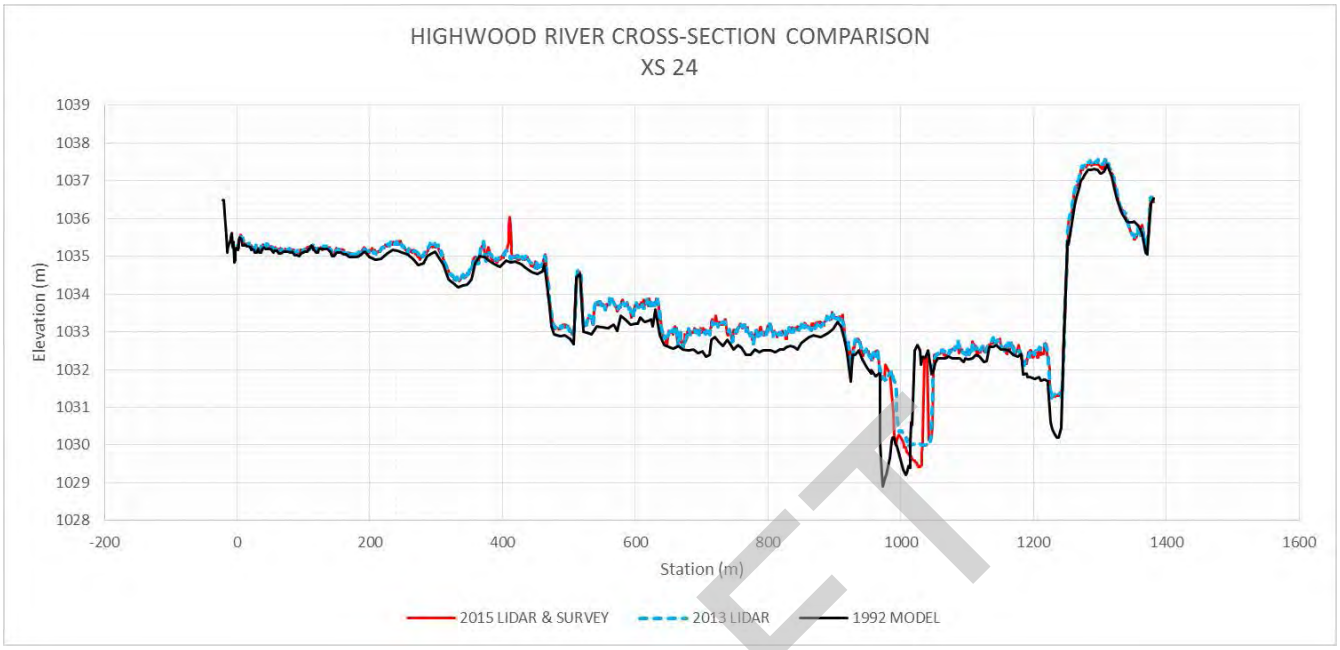


Figure A13: Highwood River Cross-Section 24 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

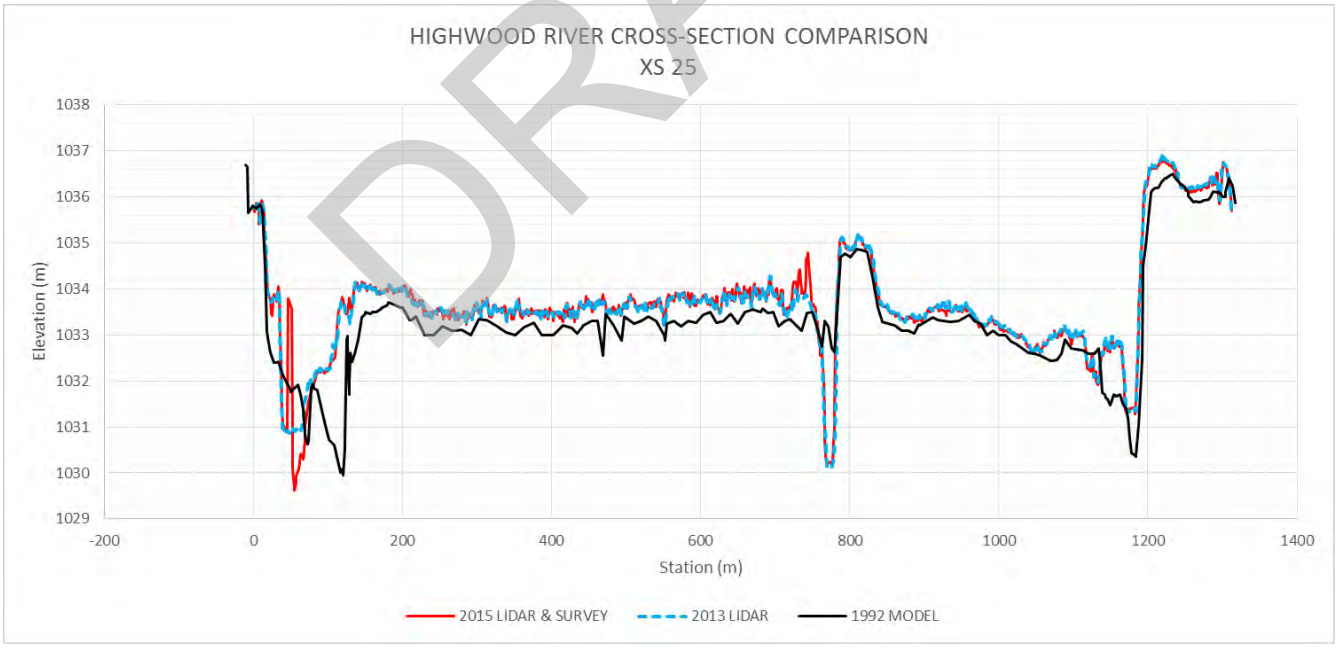


Figure A14: Highwood River Cross-Section 25 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

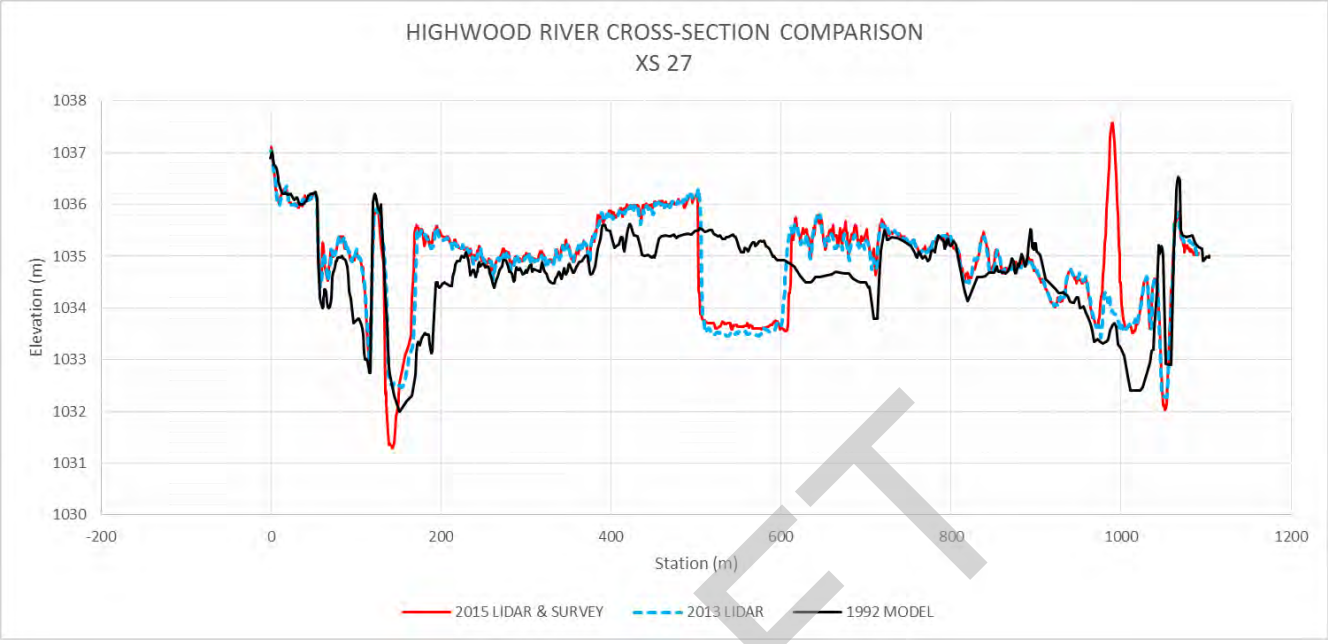


Figure A15: Highwood River Cross-Section 27 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

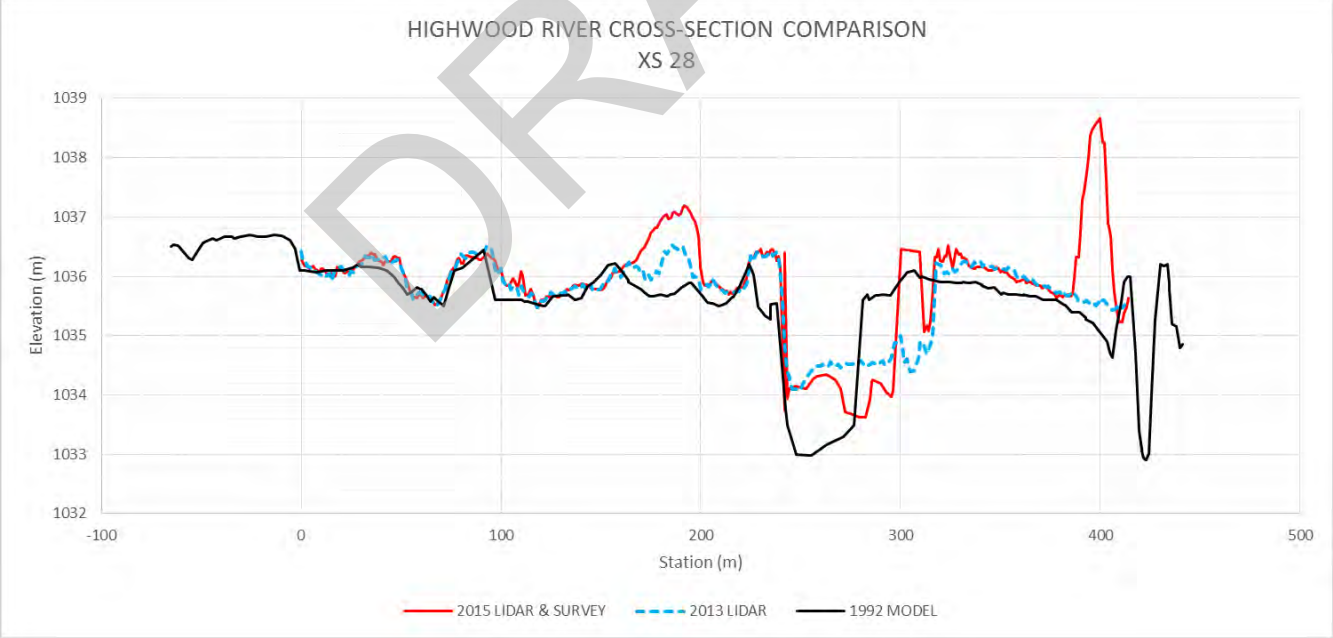


Figure A16: Highwood River Cross-Section 28 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

Figure A17: Highwood River Cross-Section 29 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

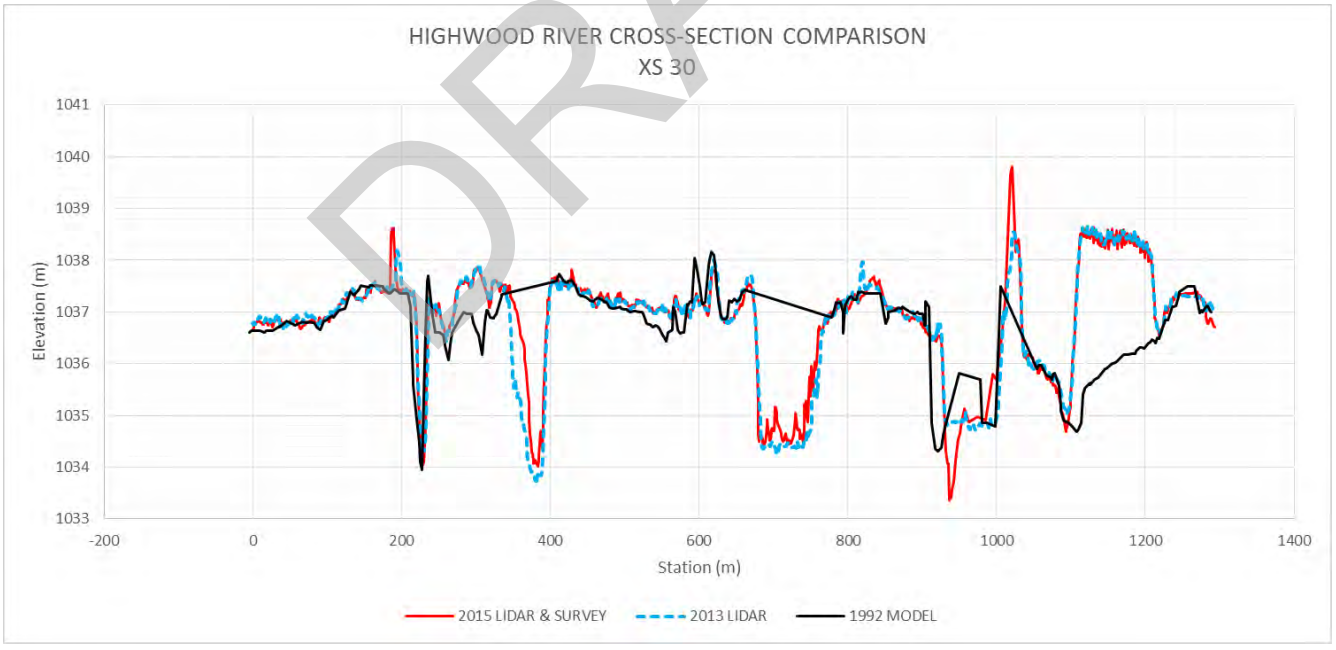


Figure A18: Highwood River Cross-Section 30 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

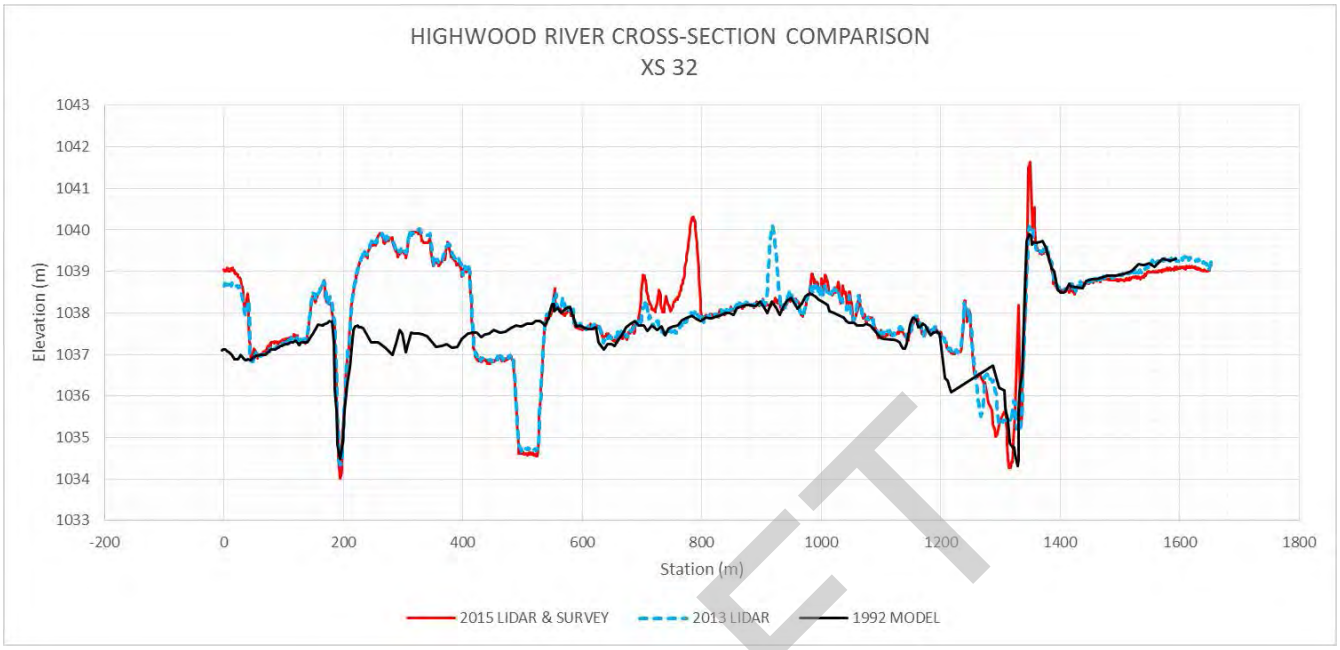


Figure A19: Highwood River Cross-Section 32 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

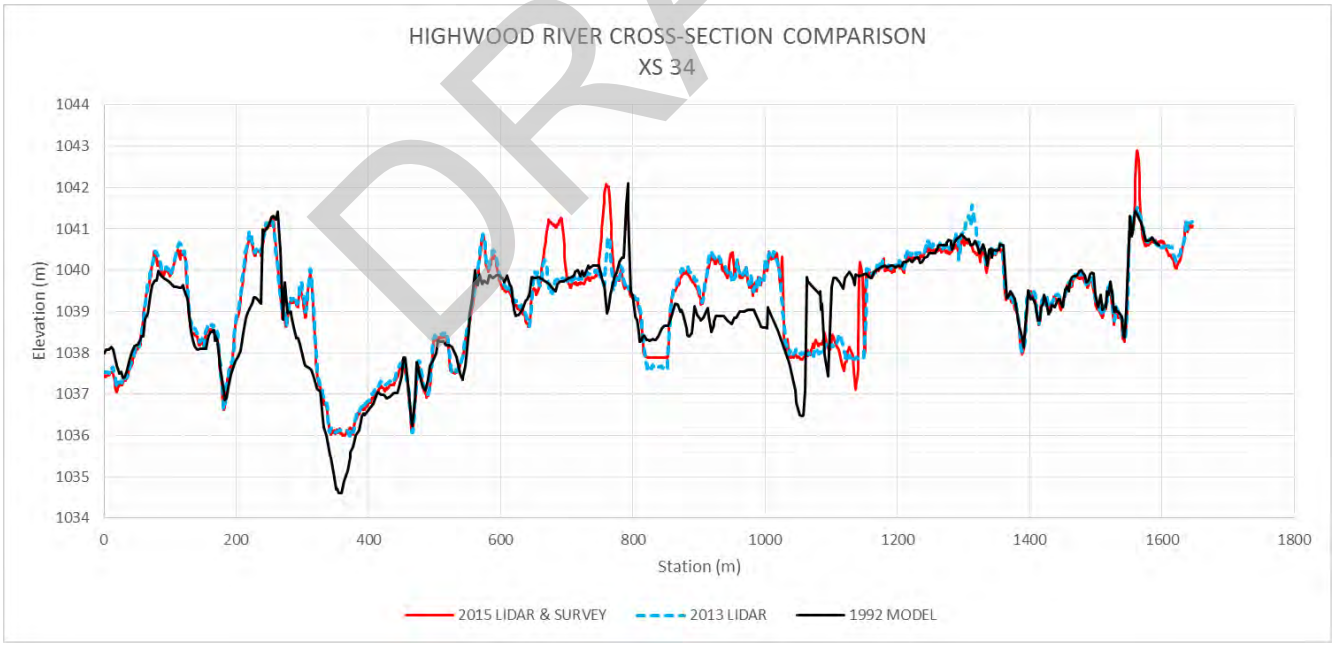


Figure A20: Highwood River Cross-Section 34 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

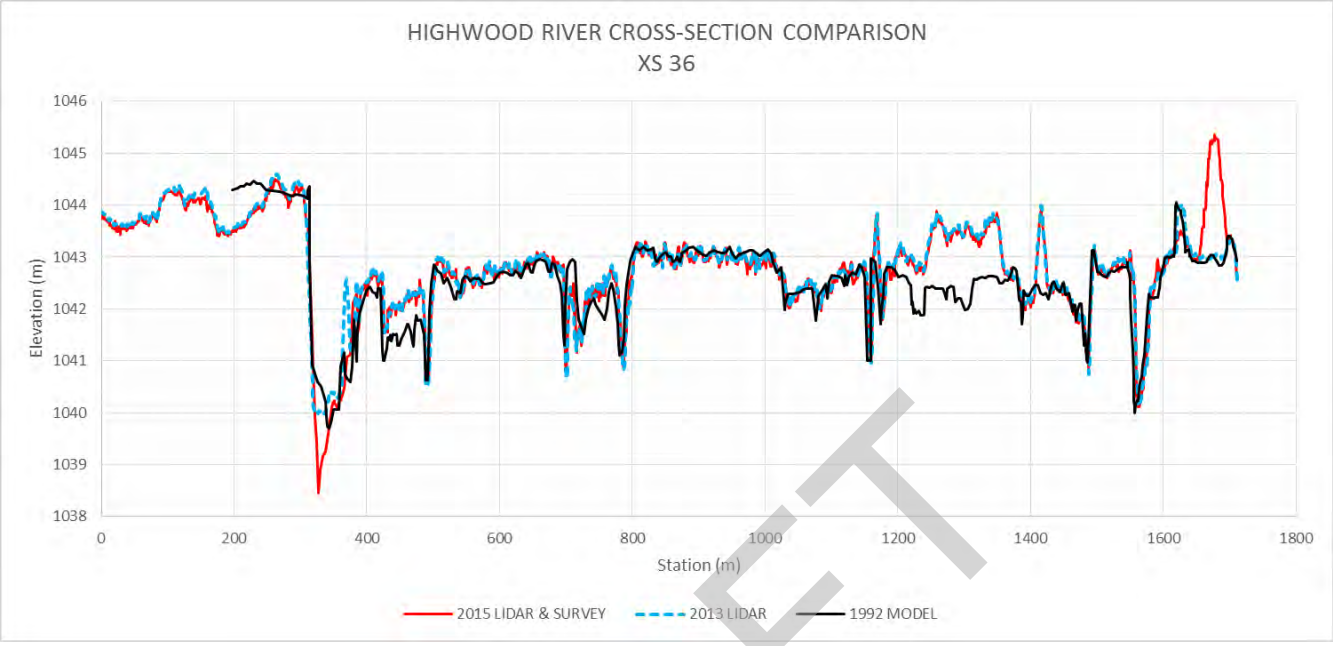


Figure A21: Highwood River Cross-Section 36 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

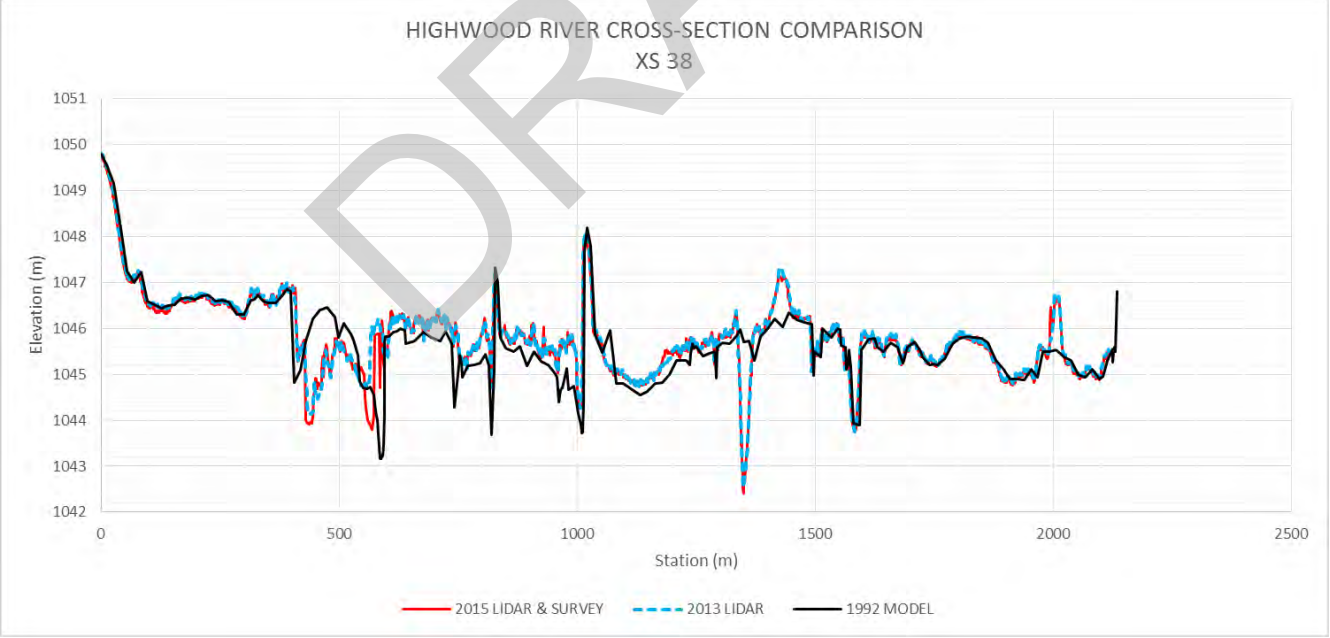
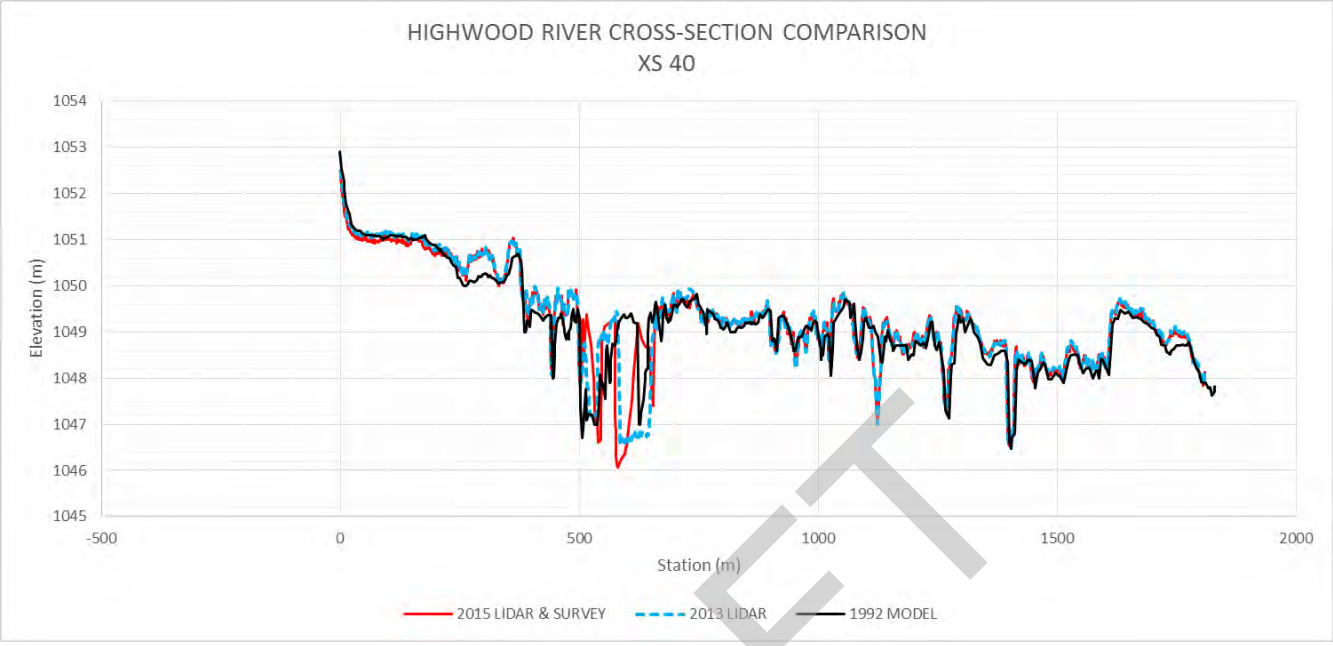


Figure A22: Highwood River Cross-Section 38 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.



Sx54rpo';[Figure A23: Highwood River Cross-Section 40 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

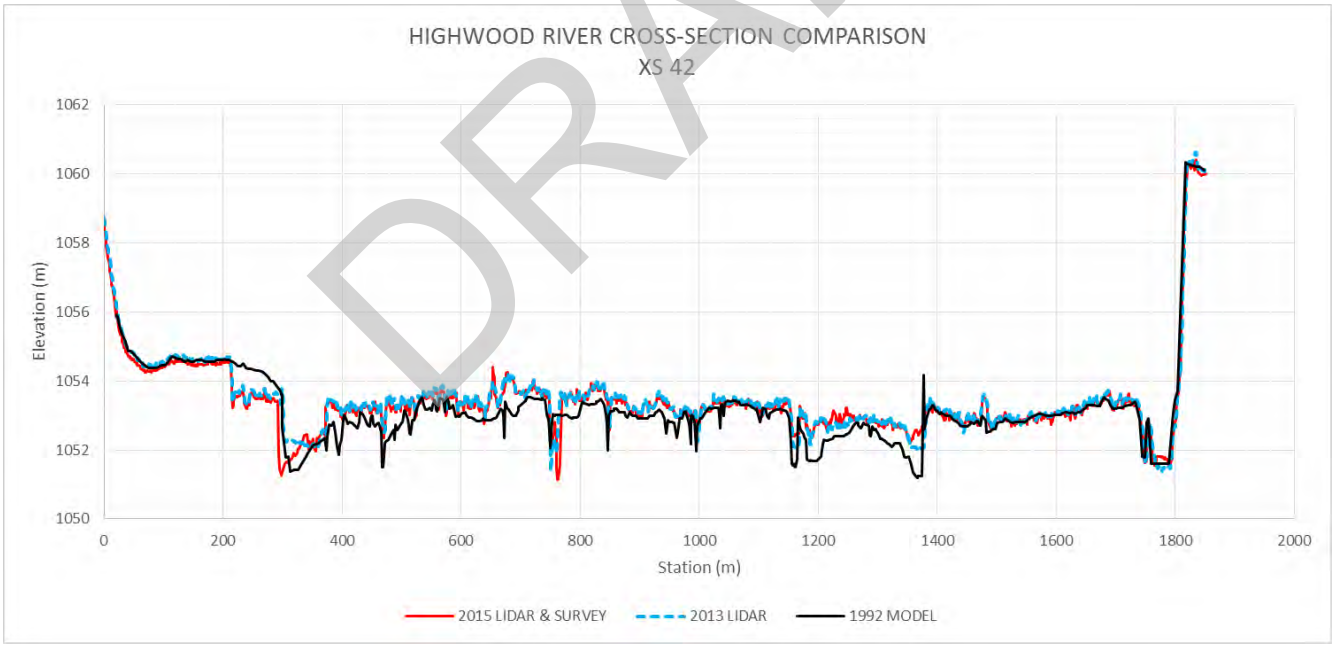


Figure A24: Highwood River Cross-Section 42 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

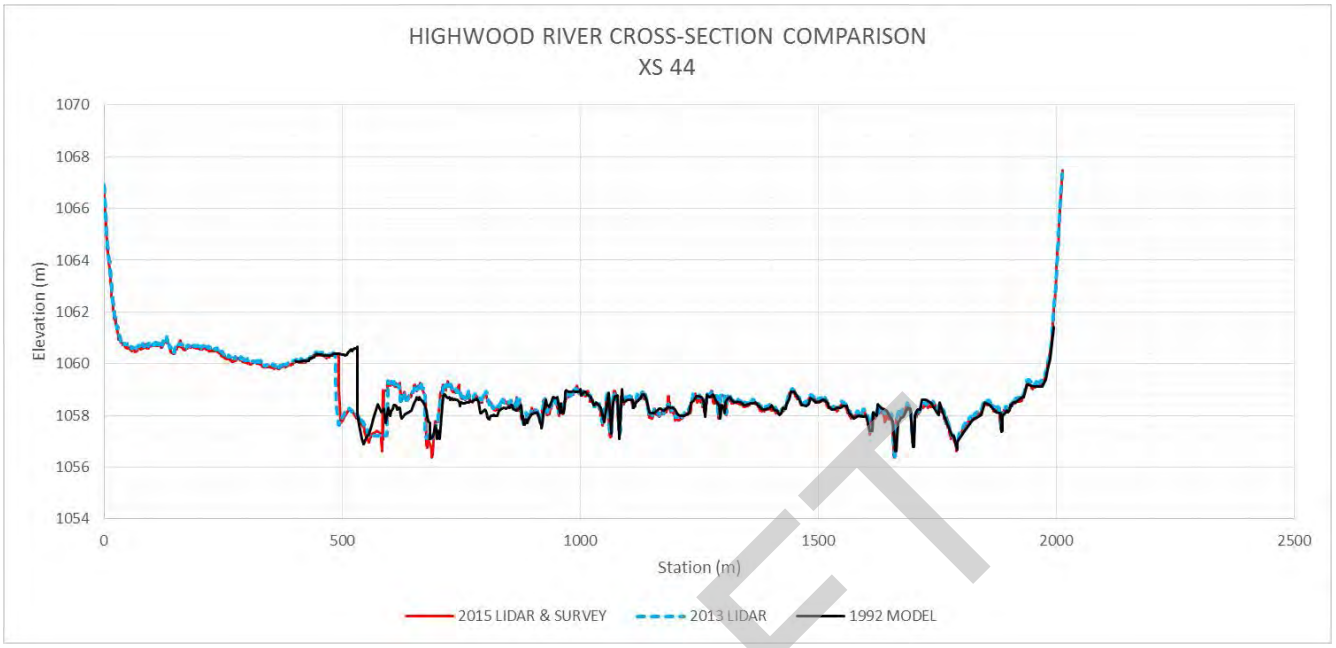


Figure A25: Highwood River Cross-Section 44 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

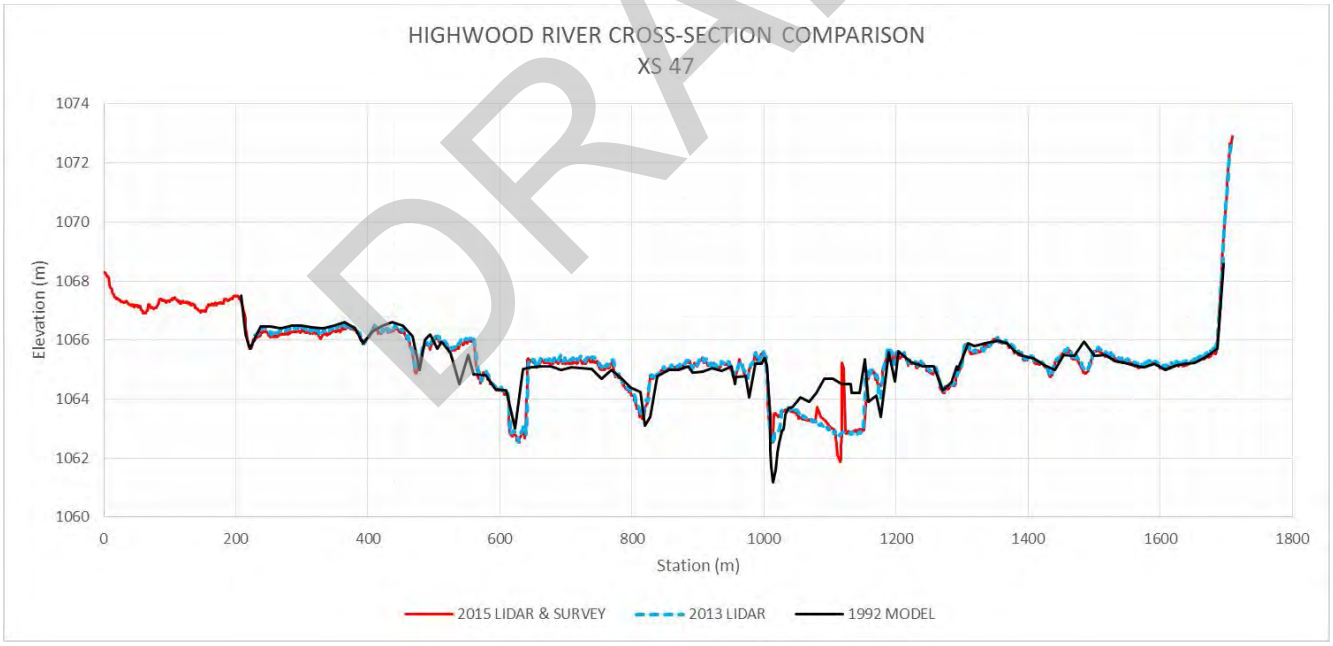


Figure A26: Highwood River Cross-Section 47 Comparison: 1992 Model, 2013 LiDAR and 2015 LiDAR and Survey.

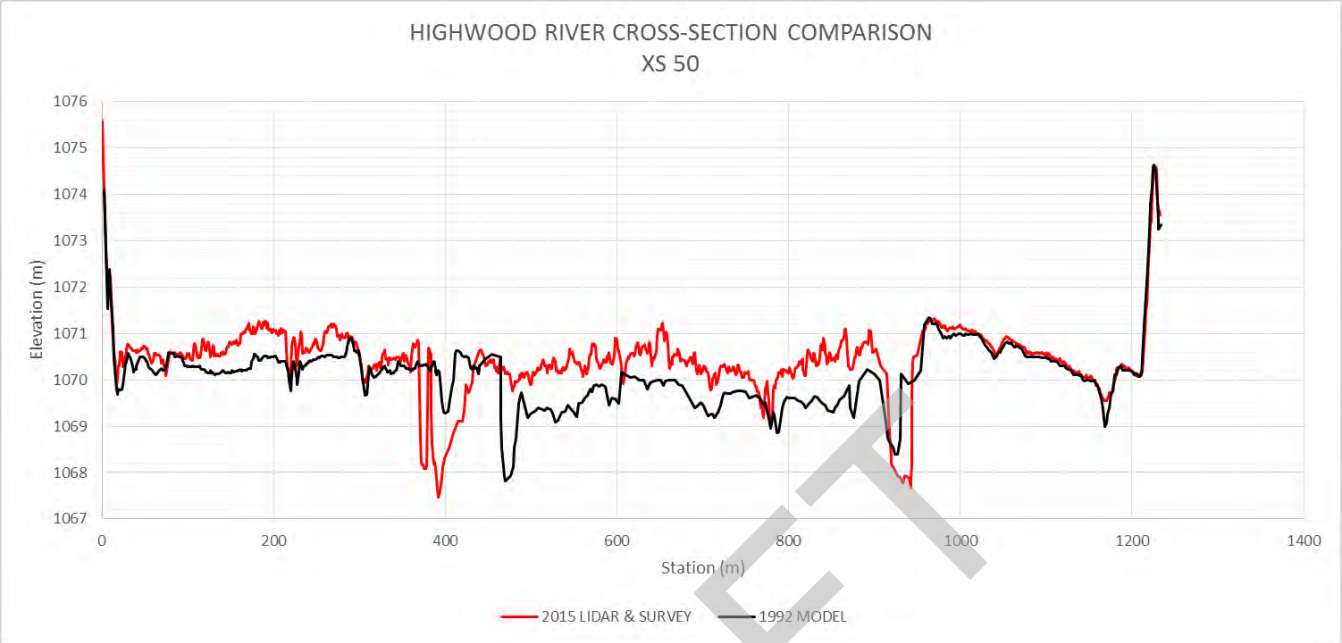


Figure A27: Highwood River Cross-Section 50 Comparison: 1992 Model and 2015 LiDAR and Survey.

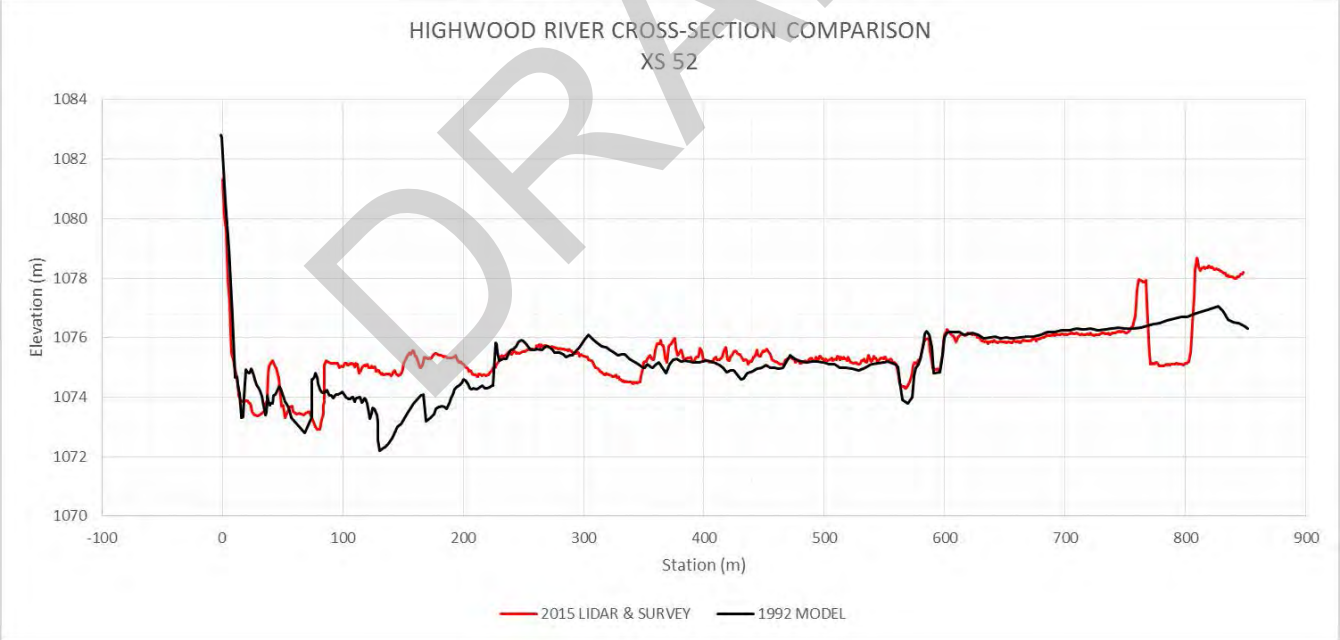


Figure A28: Highwood River Cross-Section 52 Comparison: 1992 Model and 2015 LiDAR and Survey.

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