REPORT

Channel Stability Investigation Report

Upper Red Deer River Hazard Study

Submitted to:

Alberta Environment and Parks

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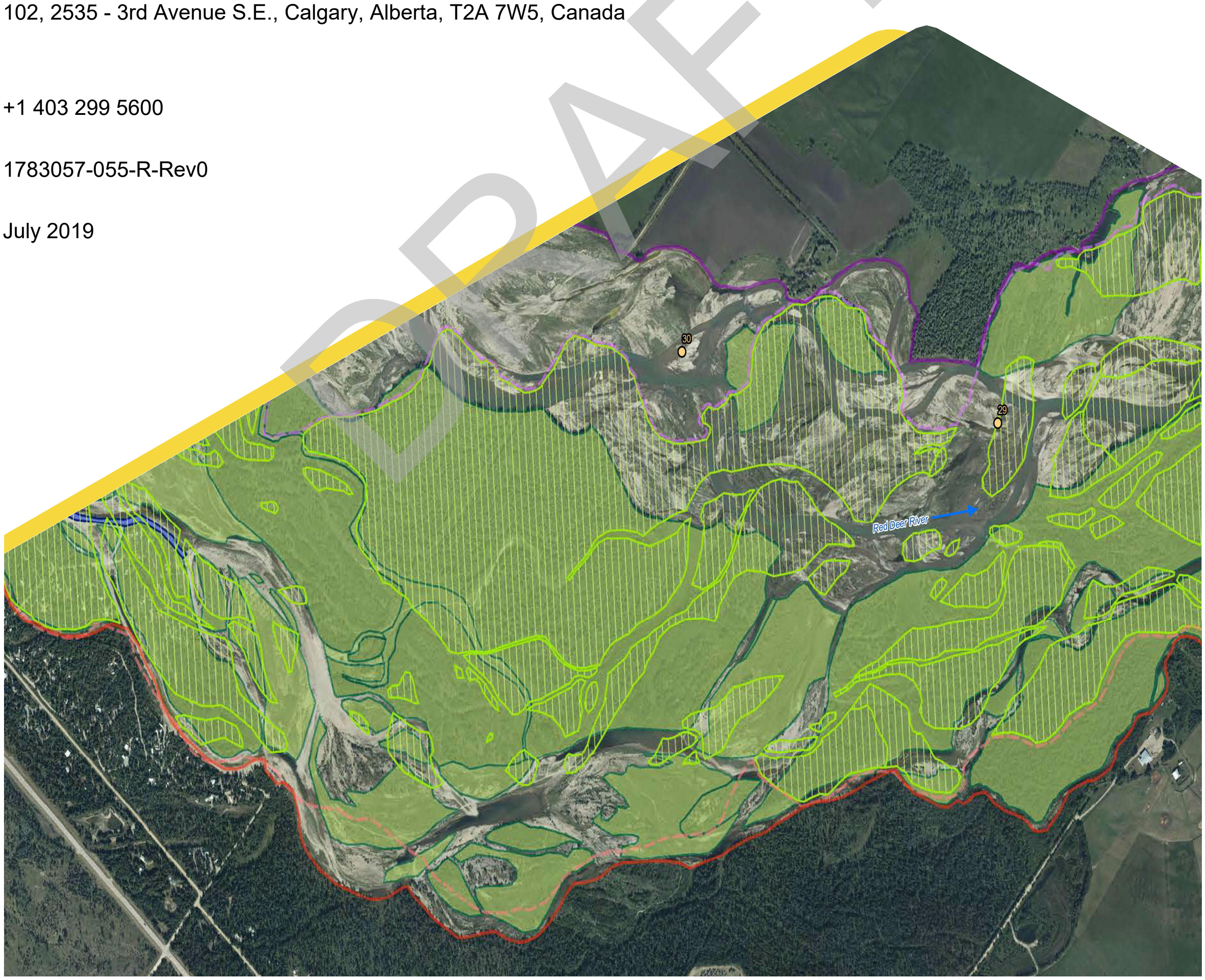

Executive Summary

Alberta Environment and Parks (AEP) commissioned Golder Associates Ltd. (Golder) in September 2017 to conduct the Upper Red Deer River Hazard Study. The primary purpose of the study is to assess and identify river and flood hazards along the Red Deer River reach from Coal Camp to Gleniffer Lake and the Bearberry Creek reach from Range Road 62 to its confluence with the Red Deer River in Sundre.

The study is conducted under the provincial Flood Hazard Identification Program (FHIP), the goals of which include enhancement of public safety and reduction of future flood damages through the identification of river and flood hazards. Project stakeholders include the Government of Alberta, the Town of Sundre, and the Counties of Mountain View, Clearwater and Red Deer, and the public.

The Upper Red Deer River Hazard Study includes multiple components and deliverables. This report documents the methodology and results of the channel stability investigation component, which provides qualitative and limited quantitative information about general channel stability along the study reaches.

The study area was divided into several stream reaches for the purpose of the channel stability investigation (see Table i).

Table i: Study Area Reaches

Stream	Reach	Reach Description	Length (km)
Red Deer River	1	Dickson Dam to STN 13+000	13
	2	STN 13+000 to STN 23+600	10
	3	STN 23+600 to James River confluence	19
	4	James River confluence to Bearberry Creek confluence	17
	5	Bearberry Creek confluence to Bearberry Prairie Natural Area	13
	6	Bearberry Prairie Natural Area to STN 85+600	13
Bearberry Creek	7	Red Deer River confluence to Bearberry Creek weir	1.4
	8	Bearberry Creek weir to upstream end of fish passage	0.3
	9	Upstream end of fish passage to Cowboy Trail	0.5
	10	Cowboy Trail to STN 13+300	11
	11	STN 13+300 to STN 14+200	0.9
	12	STN 14+200 to STN 17+100	2.9

The channel stability investigation was conducted by completing the following four tasks: channel delineation and comparison, cross section comparison, thalweg comparison, and rating curve comparison.

The channel delineation and comparison were completed by outlining the banks and mapping river features in historical and recent imagery datasets. The cross section and thalweg comparisons were completed by assessing changes between historical and recent cross section and thalweg data through qualitative and quantitative analyses. For the rating curve comparison, historical and current rating curves for a Water Survey of Canada (WSC) gauge 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 and from channel delineation were used to inform the interpretations of changes observed in the rating curves.

The results of the four tasks were used to develop criteria for channel stability based on the movement of the rivers over time and the ability of the active river channels to convey flood flows.

Summaries of each reach are as follows:

Reach 1

Reach 1 of the Red Deer River is comprised of Gleniffer Lake, which is the reservoir located upstream of Dickson Dam, and the subsequent artificial inundation that fills most of the valley. This reach is considered stable.

Reach 2

Reach 2 of the Red Deer River is characterized by a broad, multi-threaded channel corridor (the channel corridor is defined as active channel surfaces and vegetated islands that are situated between the left and right banks). Both channel migration and avulsion are common, and the reach likely experiences high sediment transport rates. This reach is considered unstable.

Reach 3

Reach 3 of the Red Deer River is typically braided. A wide active channel corridor consisting of abundant bare sediment surfaces as well as extensive evidence of channel migration and avulsion suggest that the river experiences high sediment transport rates. This reach is considered unstable.

Reach 4

Reach 4 of the Red Deer River is typically braided with a wide channel corridor and several large vegetated islands. The channel corridor is confined in the vicinity of Sundre at the upstream end of the reach but widens downstream over a distance of a few kilometres. Reach 4 appears to receive abundant sediment supply from upstream and from Bearberry Creek and is locally accumulating sediment. A wide active channel corridor consisting of abundant bare sediment surfaces as well as extensive evidence of channel migration and avulsion suggests that the river experiences high sediment transport rates. This reach is considered unstable.

Reach 5

Reach 5 of the Red Deer River is characterized by a broad, multi-threaded channel corridor with localized braiding. Historically, the channel was divided into two forks, but most flow has been diverted to the southernmost fork. This may have contributed to degradation in the reach, which was observed in the thalweg data.

A wide active channel corridor consisting of abundant bare sediment surfaces as well as extensive evidence of channel migration and avulsion suggests that the river experiences high sediment transport rates. This reach is considered unstable.

Reach 6

Reach 6 of the Red Deer River is characterized by a broad, multi-threaded channel corridor with localized braiding. A wide active channel corridor consisting of abundant bare sediment surfaces as well as extensive evidence of channel migration and avulsion suggests that the river experiences high sediment transport rates. This reach is considered unstable.

Reach 7

Reach 7 of Bearberry Creek is characterized by straight, engineered banks that confine a meandering channel with frequent islands. The banks are partly protected by riprap and do not appear to be similar in the historical and modern period, although bank erosion did occur during a flood in 2005. The channel has developed a more skewed geometry associated with a meandering planform. This reach is considered stable due to the presence of riprap, but the stream could be expected to experience more meander migration if it was less constrained by bank erosion protection.

Reach 8

Reach 8 of Bearberry Creek is straight with engineered banks. No apparent side, point, or mid-channel bars are present. The channel has cut into its bed, and its geometry has evolved from an approximately trapezoidal shape to a more skewed geometry associated with a meandering planform. This reach is considered stable due to the presence of bank protection, but the stream could be expected to experience more meander migration if it was less constrained by bank erosion protection.

Reach 9

Reach 9 of Bearberry Creek is single-threaded with no visible bars or islands. The channel was historically meandering but was straightened prior to 1992. No bank protection appears to be present. The reach appears to have experienced a minor loss to cross sectional area over the observed period and has degraded. This reach is considered unstable.

Reach 10

Reach 10 of Bearberry Creek is single-threaded with a torturous meandering planform. Occasional islands and side bars are present in this reach. Extensive migration at meander bends as well as avulsion due to meander bend cut-off were frequently observed, and the channel degraded locally. This reach is considered unstable.

Reach 11

Reach 11 of Bearberry Creek is characterized by a single-threaded, meandering channel with a low sinuosity. and the channel alignment has remained approximately stable over the observed period. There are no apparent bars or islands present. This reach is considered stable.

Reach 12

Reach 12 of Bearberry Creek is single-threaded with a torturous meandering planform. Extensive migration at meander bends as well as avulsion due to meander bend cut-off were frequently observed. Islands and side bars are rare. This reach is considered unstable.

Acknowledgements

This component of the Upper Red Deer River Hazard Study was led by Rowland Atkins. Overall project management was provided by Dr. Wolf Ploeger and direction by Dr. Dejiang Long. The channel stability investigation team included Morgan Tidd, Gaven Tang, and Kathryn De Rego with GIS support provided by Peter Thiede, Sean Kurash, and Scott Gordon.

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1.0 INTRODUCTION

1.1 Study Objectives

Alberta Environment and Parks (AEP) commissioned Golder Associates Ltd. (Golder) in September 2017 to conduct the Upper Red Deer River Hazard Study.

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The Upper Red Deer River Hazard Study includes multiple components and deliverables. This report documents the methodology and results of the channel stability investigation component, which provides qualitative and limited quantitative information regarding general channel stability along the study reaches.

1.2 Study Objectives

The primary purpose of the study is to assess and identify river and flood hazards along the Red Deer River from Coal Camp to Gleniffer Lake and Bearberry Creek from Range Road 62 to its confluence with the Red Deer River in Sundre.

1.3 Study Area and Reaches

The study area includes approximately 85 kilometres (km) of the Red Deer River and 17 km of Bearberry Creek. Streams within the study area have been divided into 12 reaches appropriate for the channel stability investigation: six along the Red Deer River and six along Bearberry Creek. The reaches are listed in Table 1 and presented in Figure 2. The approximately 3 km between STN 82+400 and Coal Camp were not evaluated in the study because they were not covered by the extent of available imagery.

Table 1: Channel Stability Investigation Reaches

Stream	Reach	Reach Description	Length (km)
Red Deer River	1	Dickson Dam to STN 13+000	13
	2	STN 13+000 to STN 23+600	10
	3	STN 23+600 to James River confluence	19
	4	James River confluence to Bearberry Creek confluence	17
	5	Bearberry Creek confluence to Bearberry Prairie Natural Area	13
	6	Bearberry Prairie Natural Area to STN 85+600	13[1]
Bearberry Creek	7	Red Deer River confluence to Bearberry Creek weir	1.5[2]
	8	Bearberry Creek weir to upstream end of fish passage	0.3
	9	Upstream end of fish passage to Cowboy Trail	0.5
	10	Cowboy Trail to STN 13+300	10
	11	STN 13+300 to STN 14+200	0.9
	12	STN 14+200 to STN 17+100	2.8

[1] approximately 3 km between STN 82+400 and Coal Camp were not evaluated (not covered by available imagery)

[2] This length does not include the historic Bearberry Creek channel, which was not categorized as modern active channel for this study.

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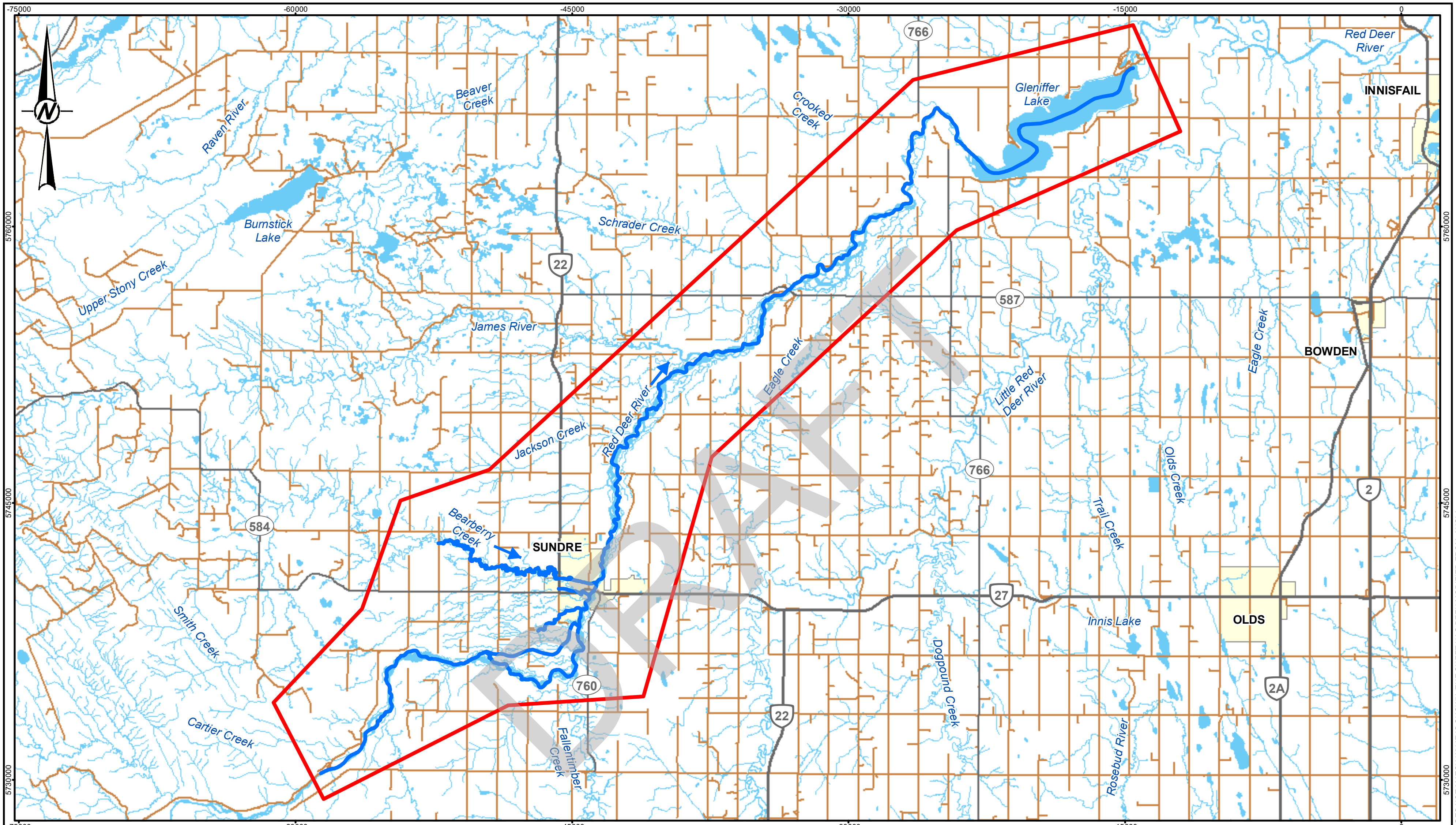

LEGEND

- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- LOCAL ROAD
- FLOW DIRECTION
- WATERCOURSE
- WATERBODY
- POPULATED PLACE
- STUDY REACH
- RIVER HAZARD STUDY AREA

0 5 10

1:300,000 KILOMETRES

REFERENCE(S)

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UPPER RED DEER RIVER HAZARD STUDY

CONSULTANT

GOLDER

YYYY-MM-DD	2019-07-22
DESIGNED	WP
PREPARED	BP
REVIEWED	RA
APPROVED	WP

TITLE
STUDY AREA OVERVIEW

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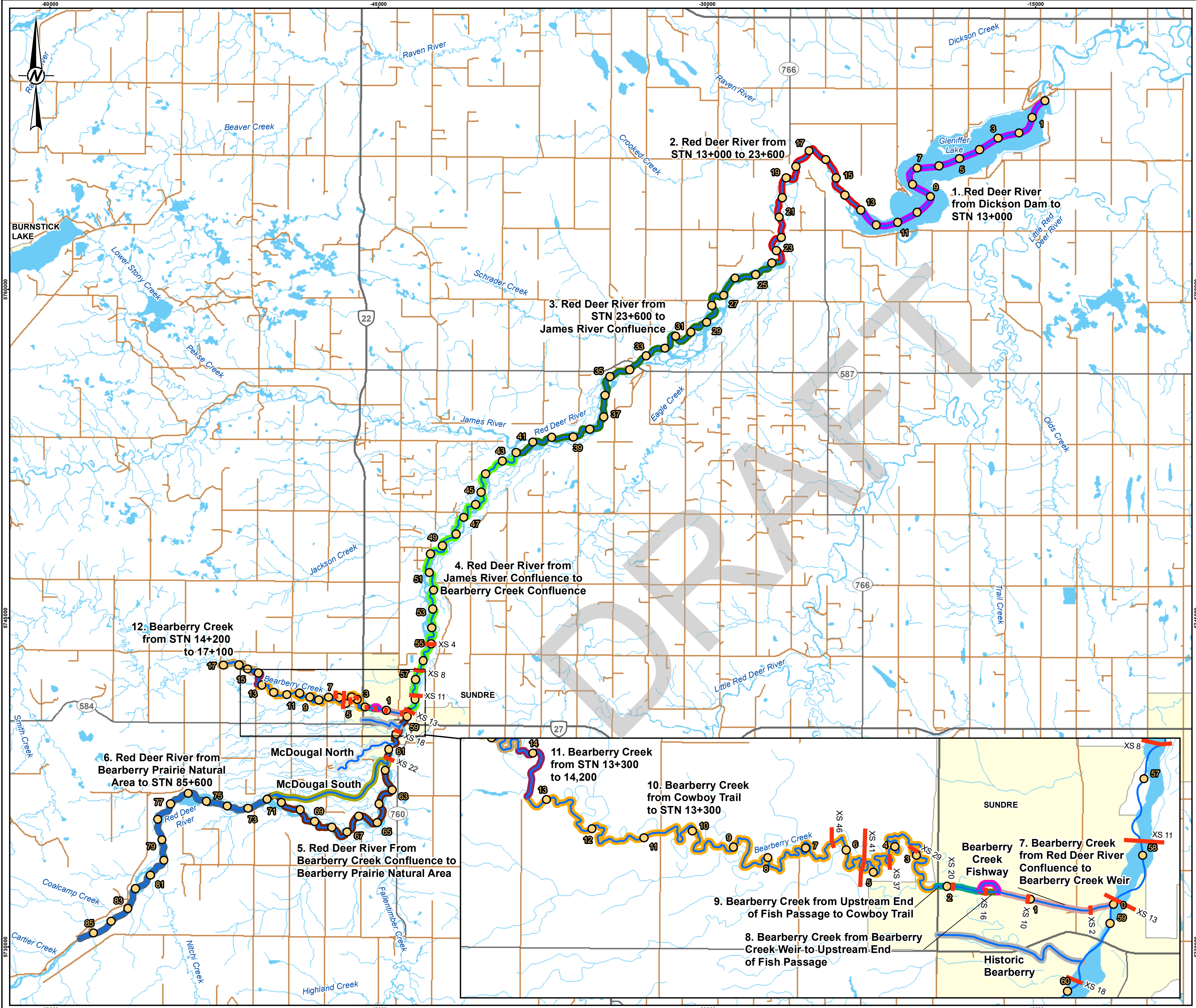

LEGEND

- RIVER STATION POST (km)
- COMPARISON CROSS SECTION
- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- LOCAL ROAD
- WATERCOURSE
- WATERBODY
- POPULATED PLACE

RIVER REACHES

- 1. RED DEER RIVER FROM DICKSON DAM TO STN 13+000
- 2. RED DEER RIVER FROM STN 13+000 TO STN 23+600
- 3. RED DEER RIVER FROM STN 23+600 TO JAMES RIVER CONFLUENCE
- 4. RED DEER RIVER FROM JAMES RIVER CONFLUENCE TO BEARBERRY CREEK CONFLUENCE
- 5. RED DEER RIVER FROM BEARBERRY CREEK CONFLUENCE TO BEARBERRY PRAIRIE NATURAL AREA
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- MCDOUGAL SOUTH
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- 9. BEARBERRY CREEK FROM UPSTREAM END OF FISH PASSAGE TO COWBOY TRAIL
- 10. BEARBERRY CREEK FROM COWBOY TRAIL TO STN 13+300
- 11. BEARBERRY CREEK FROM STN 13+300 TO 14+200
- 12. BEARBERRY CREEK FROM STN 14+200 TO 17+100

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REFERENCE(S)

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PROJECT
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TITLE
RIVER REACHES

CONSULTANT

GOLDER

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APPROVED	WP

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1.4 Scope of Work

The scope of the channel stability investigation component of the study includes the following activities:

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

2.0 AVAILABLE DATA

2.1 Aerial Imagery

Aerial imagery obtained for this study included recent imagery collected in 2018 as well as historical imagery consisting of photos collected in 1961 and 1962. Both imagery sets provide full coverage of the study area, except for a few kilometres on the upstream end of the Red Deer River. A summary of imagery specifications is presented in Table 2. Details on image preparation for the historical imagery are presented in Appendix B.

Table 2: Summary of Aerial Imagery

Era	Date(s) of Collection	Scale	Resolution (m)	Source	Accuracy (m)
Recent	13-Jul-2018	-	0.30	Provided by AEP	0.9 m (adjustment accuracy)
Historical	18-Jul-1962, 14-May-1963, 13-Jun-1963	1:31,680	0.64	Provided by AEP	6 m

2.2 Cross Section and Thalweg Data

Cross section data was obtained from two sources: (1) historical cross sections were compiled from a flood risk mapping study in the vicinity of Sundre, AB (AEP, 1997), and (2) modern cross sections were obtained from a recent digital elevation model (DEM) derived from 2017 LiDAR data provided by AEP and river survey data collected in 2017 (Golder, 2019a). The historical cross sections were collected in 1992 and provide complete coverage of Reaches 7, 8, and 9, as well as approximately one quarter of Reach 4, one third of Reach 5, and one third of Reach 10. Modern cross section data is available for the entire study area. Thalweg data was extracted from the cross sections.

A summary of the topographic data is presented in Table 3.

Table 3: Summary of Cross Section and Thalweg Data

Dataset	Reach or Subreach	Date(s) of Collection	Resolution (m)	Source	Accuracy (m)
1992 survey data	Complete coverage of 7, 8, and 9, and partial coverage of 4, 5, and 10 in the vicinity of Sundre	Summer, 1992	variable	AEP (1997)	unknown, but data reported to centimetre scale
2017 survey data	Complete coverage of 1-12	September/ October 2017	variable	Golder (2019a)	+/- 0.05 (RTK survey) and +/- 0.10 (RTK/ADP combination)

2.3 Rating Curve Data

Current and historic rating curves were obtained from the Water Survey of Canada (WSC) for the gauge Bearberry Creek near Sundre (05CA011). The gauge was established in 1976 in Reach 7, approximately 1 km upstream of the Bearberry Creek mouth. In 2004, it was moved approximately 1 km upstream to the Cowboy Trail bridge crossing at the boundary between Reaches 9 and 10. Rating curve data are available from 1997 to the present.

One rating curve was obtained from AEP for the Red Deer River at Sundre (05CA010), however the station was discontinued in 1973 and no other historical rating curve data are available. Therefore, rating curve data from this station were not included in the analysis.

3.0 METHODS

3.1 Channel Delineation and Comparison

The channel delineation and comparison were conducted using orthorectified and georeferenced (triangulated) historical air photos viewed using ArcMap™ software. Historical air photos were reviewed using stereoscopic image display software. For the modern period, the 2018 orthophoto data provided by AEP were viewed in conjunction with contour data derived from the 2017 LiDAR DTM provided by AEP and from the 2017 Golder survey (Golder, 2019a). Coverage, resolution and scale of the imagery are discussed in Section 2.1. Channel features were delineated directly onscreen from historical and recent aerial imagery at a scale of 1:2,000. Mapped features include:

- Active channel (polygon format): Surfaces within the active channel lack established vegetation (e.g., bushes and trees over approximately 0.5 meters in height) and are expected to typically convey flow during a 2-year flood event. The active channel may be composed of a dominant channel, one dominant channel that carries the majority of flow along with one or more sub-dominant channels, or multiple sub-dominant channels.
- Banks (line format): The left and right banks are defined as the left-most and right-most margins of the active channel, respectively.
- Vegetated islands (polygon format): Vegetated islands are defined as patches of established vegetation that are situated between the left and right banks.
- Bank protection (polygon format): Bank protection includes man-made features designed to stabilize channel banks, such as riprap.

Once mapped, the digital channel margins were exported into an ArcGIS 10.3 (ArcMap) database with geospatial attributes.

Visual comparisons of the historically-imaged and most recently-imaged channels were undertaken on the 2018 orthophoto imagery provided by AEP. The comparisons were focused on identifying characteristics of channel instability, which include:

- Presence of channel morphologies typically characterized by instability (e.g., braided and wandering morphologies).
- Expansion, contraction, and/or migration of the channel corridor. The channel corridor consists of terrain (including both active channel and vegetated islands) that is situated between the left and right banks.
- Reorganization within the channel corridor, including migration or avulsion of dominant and sub-dominant channels, formation or loss of islands, or changes in channel morphology.

Floodplain reactivation was quantified to augment the visual channel comparison. Floodplain reactivation is defined as the percentage of active channel mapped for the modern period that was not active channel during the historical period. It is a metric of the amount of channel change, where higher values of reactivation typically indicate more unstable conditions. For reaches with wandering or braided morphology, visual comparison of channel change is more difficult due to the complexity of the channel corridor. Therefore, in these reaches, the change in active channel width was estimated using samples of the mapped channel surfaces determined by approximately evenly spaced transects. Transects were not created to estimate active channel width change for reaches with typically single-threaded morphology because the visual comparison was deemed sufficient.

No attempt was made to quantify the width of the meander belt, which is defined as the portion of floodplain across which the channel can be expected to shift on decadal or longer timescales. Detailed mapping of the meander belt was outside of the scope of work but would be a useful metric for high-level erosion hazard assessments in the future. The meander belt is typically as wide or wider than the active channel corridor.

A select set of figures were developed to highlight typical reach characteristics. These figures are accompanied by a technical summary discussing the general nature of general lateral stability in the study area (e.g., observations that lateral 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 study area. For the analysis, a subsample of 14 representative cross sections in Reaches 4-5 and 7-10 were selected for review in detail (see Figure 2 for cross section locations). The selected representative cross sections were compared with estimates of meander spacing to validate coverage of major river features. Cross section comparisons were not completed for Reaches 1-3, 6, and 11-12 because historic cross section data were not available.

Qualitative and quantitative analyses were conducted on the representative cross sections. The qualitative analysis included review and documentation of cross section features such as single thread or multiple thread channels, left-handedness or right-handedness (i.e., the deepest part being located on the left[1] or right side of the

[1] When describing cross section stationing or properties, left and right are defined relative to an observer facing downstream.

river channel), skewness (i.e., cross sections with a uniform geometry or leaning to left or right), 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 for each cross section. These parameters were used to determine channel type and changes in hydraulic capacity using simple hydraulic relationships. Few cross sections were suitable for comparison due to the limited coverage of historical data. Therefore, the significance of recorded changes was not tested with statistical analysis.

3.3 Thalweg Profile Comparison

The thalweg is the line that passes through the deepest part of the river in the downstream direction. It links the deepest areas of the river together and is a representative feature of channel geometry. Historical and current thalweg profiles were reviewed as part of this analysis. Where both historical and modern coverage was available, increases or decreases in thalweg slope were evaluated and documented in context with reviewed cross sections and major river features. Areas of scour or degradation (bed elevation decreases) and sedimentation or aggradation (bed elevation increase) were identified, and reach-averaged net bed volume changes were calculated.

Due to the limited coverage of historical data, a plan view comparison of the thalweg to evaluate lateral migration was not created. Migration of the river channel as documented in the channel bank and cross section comparisons is deemed sufficient to address lateral migration.

3.4 Rating Curve Comparison

Rating curves at hydrometric gauges can be altered due to changes in main channel geometry or riverbed elevation. The passage of sediments through the river and the mobile nature of many riverbeds can cause bed levels to increase and decrease in response to natural river changes and flood events.

Available rating curve data for a gauge on Bearberry Creek was provided by WSC as described in Section 2.3. The historical and current rating curves were compared, in context with observed changes in the river and features of nearby cross sections. Information collected from the comparison of channel banks, cross sections, and thalweg profiles was used to inform the interpretation of changes observed in the rating curves.

3.5 Classification of reach stability

Results of the channel delineation, cross section, thalweg, and rating curve comparisons were used to develop criteria for channel instability and to designate each reach as stable or unstable. For the purposes of this study, unstable channels are those for which:

- High levels of floodplain reactivation occur over the scale of decades. The definition of a high level of reactivation is provided in Section 4.1 (below).
- Trends in bed elevation change or cross sectional area suggest that the ability of the active channel to convey flood flows may be decreasing.

The criteria are not designed to be universal and are applicable to this study only. The designation of stable or unstable reaches is not specifically related to whether the reach is in equilibrium. For example, a degrading channel may be classified as stable for this analysis, even though it is not in equilibrium, because it does not meet the criteria listed above.

4.0 RESULTS

4.1 Criteria for channel stability

The thresholds between unstable and stable channels based on observations from the channel delineation and comparison, cross section comparison, thalweg comparison, and rating curve comparison are presented in Table 4. Reaches where 40% or more of the modern active channel was mapped as floodplain in the early 1960s typically displayed indicators of channel instability, including migration of the channel corridor, migration and avulsion of dominant and sub-dominant channels within the active channel, scour and/or formation of vegetated islands, and indications that the stream carries a high sediment load. These reaches are classified as unstable.

Channels are also considered unstable if there are signs that the cross sectional area of the active channel is decreasing. This decrease may result from aggradation, channel narrowing, or a loss of sub-dominant channels.

Indicators of lateral channel stability and the floodplain reactivation percentage are described for each reach in Section 4.2. Changes to cross section area are described in Sections 4.3 through 4.5.

Table 4: Criteria for Channel Stability and Instability

Geomorphic Metric	Sign of Stability	Sign of Instability
Floodplain reactivation percentage	Percentage of 2017 active channel that was vegetated in the early 1960s is less than 40%	Percentage of 2017 active channel that was vegetated in the early 1960s is greater than 40%
Change in cross sectional area	Cross sectional area has remained stable or has increased	Cross sectional area has decreased

4.2 Channel Delineation and Comparison

Observations from the channel mapping and comparison analysis for each sub-reach are listed in Table 5 and presented in Figure 3 through Figure 13. The summary of channel stability for all reaches is presented in Figure 14. Summaries for each reach are presented below.

4.2.1 Reach 1

Reach 1 (Red Deer River), which extends from Dickson Dam to STN 13+000, is typically submerged by Gleniffer Lake. In the historical period, the channel exhibited a wandering (transitional between braided and single-threaded) planform. This wandering platform contained narrow, single-threaded sections separated by wider channel corridors. The wider channel corridor areas contained stable islands. A sub-section of Reach 1 is presented in Figure 3.

Reach 1 is considered typically laterally stable due to the presence of the reservoir.

4.2.2 Reach 2

Reach 2 (Red Deer River), which extends from STN 13+000 to STN 23+600, is typically wandering with a wide channel corridor and abundant sub-dominant channels. The channel corridor orientation in this reach transitions sharply from north to southeast as a result of valley forcing, and it is situated adjacent to a bluff over approximately half its length. The width of active channels within the reach typically narrowed by up to approximately 50% (Figure 15). The reach is characterized by prominent movement of the channel corridor as well as a large turnover of vegetated islands over the observed period. Approximately 48% of active channel surfaces in 2018 were vegetated in the early 1960s.

A subset of this reach is presented in Figure 4. The dominant channel has migrated up to 300 metres (m) over the observed period, and the channel corridor widened up to 300 m due to the emergence of a new sub-dominant channel.

Reach 2 is considered typically laterally unstable due to the high level of floodplain reactivation.

4.2.3 Reach 3

Reach 3 (Red Deer River), which extends from STN 23+600 to the James River confluence, is typically braided with a wide channel corridor and common vegetated islands. The channel corridor has migrated on the outside of some bends over time, although the alignment appears to be more stable over time at locations where the channel corridor is forced against bluffs. Visual evidence of channel migration and avulsion were frequently noted over the observed period. The active channel widened in some locations up to approximately 75% but primarily narrowed by up to approximately 50% (Figure 15). Approximately 52% of active channel surfaces in 2018 were vegetated in the early 1960s.

A sub-reach demonstrating lateral instability of the channel corridor is presented in Figure 5. The channel corridor is unconfined, and it has widened up to almost 600 metres. The dominant channel has shifted approximately 1,000 m from the right to the left edge of the channel corridor. There appear to be fewer vegetated islands in the modern period than the historical period, suggesting that the channel has gone through a recent period of increased instability.

A sub-reach experiencing less lateral movement of the channel corridor is presented in Figure 6. This sub-reach is constrained by bluffs on the outer (left) bank, and the channel corridor margins remained relatively consistent over the observed period except for some minor fluctuations on the right bank due to the creation and abandonment of sub-dominant channels. The general orientation of the dominant channel has remained relatively consistent over the observed period, although channel migration of up to 120 m and avulsions on sub-dominant channels were observed.

Reach 3 is considered typically laterally unstable due to the high level of floodplain reactivation.

4.2.4 Reach 4

Reach 4 (Red Deer River), which extends from the James River confluence to the Bearberry Creek confluence, is typically braided with several large islands. The channel corridor is confined in the vicinity of Sundre at the upstream end of the reach but widens downstream over a distance of a few kilometres. The channel corridor margins have typically narrowed over the observed period due to the abandonment of sub-dominant channels on the periphery of the channel corridor, but the active channel width has widened by up to approximately 50% (Figure 15). The amount of channel change within Reach 4 is high over the observed period. Approximately 42% of active channel surfaces in 2018 were vegetated in the early 1960s.

A sub-reach demonstrating the lateral instability of Reach 4 is presented in Figure 7. The channel corridor narrowed by up to 750 m due to the abandonment of a sub-dominant channel. However, the active channel shifted to the east approximately 215 m and widened by up to approximately 180 m.

A sub-reach highlighting confined conditions at the upstream end of the reach is presented in Figure 8. The channel corridor narrowed by up to approximately 200 m, but the dominant channel migrated approximately 100 m to the east. The greater majority of the vegetated islands were scoured away during the observed period.

Reach 4 is considered typically laterally unstable due to the high level of floodplain reactivation.

4.2.5 Reach 5

Reach 5 (Red Deer River), which extends from the Bearberry Creek confluence to the Bearberry Prairie Natural Area, is comprised of northern and southern forks divided by a large vegetated island. The two forks join approximately 2.3 km upstream of the confluence of Upper Red Deer River and Bearberry Creek. Most of the channel flow is carried by the southern fork, which is typically wandering with localized braiding. Approximately 49% of active channel surfaces in Reach 5 in 2018 were vegetated in the early 1960s.

A representative sub-section of the southern fork is presented in Figure 9. The right margin of the channel corridor shifts to the south up to 200 m, and avulsion and channel migration of the dominant channel are prevalent.

An example of the northern fork (McDougal south) is also presented in Figure 9. In the historical period, it was typically wandering. The active channel was dissected by large vegetated islands. By the modern period, most of the flow has been diverted to the southern fork, and most channel sections have begun to stabilize. However, a defined segment of active channel emerges at the downstream end of the northern fork, so the fork is still considered active.

Downstream from the juncture of the northern and southern forks, the channel corridor becomes confined, apparently due to the Highway 27 bridge. A sub-reach highlighting these conditions is presented in Figure 8. Bank protection is present on both sides of the channel corridor. A new sub-dominant channel has formed on the right bank approximately 350 m upstream of the Highway 27 bridge. Channel morphology in the reach appears to be more braided in the modern period than in the historic period, and the channel corridor has shifted to the west approximately 50 m. The dominant channel has migrated across the channel corridor in multiple locations, including under the bridge.

Reach 5 is considered typically laterally unstable due to the high level of floodplain reactivation.

4.2.6 Reach 6

Reach 6, which extends from the Bearberry Prairie Natural Area to STN 85+600, typically exhibits a wandering planform with localized braiding. The channel corridor is situated near a series of bluffs along the right side of the valley. Over the observed period, the corridor narrowed locally and shifted toward the middle of the valley. In general, the active channel widened, by over 100% in some locations (Figure 15). Approximately 45% of active channel surfaces in 2018 were vegetated in the early 1960s.

A subset of this reach is presented in Figure 10. The channel corridor shifted to the north approximately 140 m and narrowed locally by approximately 200 m due to the abandonment of a sub-dominant channel. The right bank has remained stable on the downstream portion of the reach, where it is situated adjacent to bluffs. The active channel appears to be more single-threaded in the modern period than it was in the historical period, and the dominant channel has migrated on the order of 100 to 300 m throughout the sub-reach.

Reach 6 is considered typically laterally unstable due to the high level of floodplain reactivation.

4.2.7 Reach 7

Reach 7, which extends along Bearberry Creek from its confluence with Upper Red Deer River to a weir near the Bearberry Creek fish passage, typically exhibits a straight to meandering planform with frequent islands. The banks have been artificially straightened and appear to be protected by riprap. The alignment of the right and left banks are similar in the 1960s and 2018 photos, and only 24% of active channel surfaces in 2018 were vegetated in the historical period. However, substantial bank erosion did occur at the upstream end of the reach during flooding in 2005. Photos provided by the town of Sundry and presented in Golder (2019b) show bank erosion on the right bank just downstream of the Bearberry Creek weir and on the left bank approximately 200 m downstream of the weir. The riprap observed along the eroded areas appears to be a different colour than the surrounding riprap observed in the modern imagery, suggesting that the eroded areas were repaired prior to 2018. Reach 7 is presented in Figure 11. Over the observed period, the islands have typically shifted upstream and become more vegetated.

Reach 7 is considered typically laterally stable due to the low level of floodplain activation and the presence of riprap, but could become unstable if the riprap is not adequate or maintained.

4.2.8 Reach 8

Reach 8, which extends from the Bearberry Creek weir to the upstream end of the fish passage, was meandering and highly sinuous during the historical period. The channel has been straightened, and a fish passage has been constructed in the vicinity of the historical channel. No apparent side, point, or mid-channel bars are present. Rip rap appears to be present along both banks. 75% of active channel surfaces in 2018 were vegetated in the early 1960s, but the high amount of floodplain reactivation is attributed to channel straightening and construction of the fish passage. Channel mapping for Reach 8 is presented in Figure 11.

Reach 8 is considered typically laterally stable due to the presence of riprap, but could become unstable if the riprap is not adequate or maintained.

4.2.9 Reach 9

Reach 9, which extends from the upstream end of the fish passage to Cowboy Trail (Highway 22), was meandering and highly sinuous during the historical period, but the channel was straightened over the observed period. The channel is typically single-threaded, with no bars or islands present. No bank protection was observed along the channel margins. 63% of active channel surfaces in 2018 were vegetated in the early 1960s, although some floodplain reactivation can be attributed to channel straightening. Channel mapping for Reach 9 is presented in Figure 11.

Since the natural channel alignment for Reach 9 is meandering and no bank protection appears to be present, high levels of floodplain reactivation are expected in the future. Therefore, Reach 9 is considered typically laterally unstable.

4.2.10 Reach 10

Reach 10, which extends from Cowboy Trail to STN 13+300, is typically single threaded with a torturous meandering planform. Occasional islands and side bars are present. Evidence of both channel corridor migration and meander bend cut-off was frequently observed. 63% of active channel surfaces in 2018 were vegetated in the early 1960s.

Figure 12 shows a representative sub-reach where channel corridor migration is prevalent. Migration is typically greatest near the apex of meander bends, where the channel corridor moved approximately 20 to 30 m over the observed period. The channel width appears to have remained approximately constant over time.

A sub-reach showing typical meander bend cut-offs is also presented in Figure 12. Channel bends have been cut off in two locations, abandoning approximately 400 m and 650 m of channel, respectively. In this sub-reach, channel migration at outer bends was typically approximately 3 to 35 m, with one bend just downstream of a meander cut-off migrating approximately 100 m to the south.

Reach 10 is considered typically laterally unstable due to the high level of floodplain reactivation.

4.2.11 Reach 11

Reach 11, which extends from STN 13+300 to STN 14+200, is typically characterized by a single-threaded, meandering channel with a low sinuosity. No apparent bars or islands are present, and the left and right bank alignments have remained approximately stable over the observed period. Only 23% of active channel surfaces in 2018 were vegetated in the early 1960s. Channel mapping for Reach 11 is presented in Figure 13.

Reach 11 is considered typically laterally stable due to the low level of floodplain reactivation.

4.2.12 Reach 12

Reach 12, which extends from STN 14+200 to STN 17+100, is typically single-threaded with a torturous meandering planform. Small islands and side bars are rarely present. Evidence of both channel corridor migration and meander bend cut-off was frequently observed. 44% of active channel surfaces in 2018 were vegetated in the early 1960s.

Figure 13 shows a representative sub-reach where channel corridor migration and meander cut-offs are both prevalent. Migration is typically greatest near the apex of meander bends, where the channel moved approximately 10 m over the observed period. A channel cut-off has also occurred, abandoning approximately 100 m of channel. There appears to have been some fluctuation in channel width; in some locations, it is approximately 12 m narrower, while on others it widened by a few metres.

A second sub-reach showing typical meander bend cut-offs is presented in Figure 13. Channel bends have been cut off in two locations, abandoning approximately 300 m and 700 m of channel, respectively. In this sub-reach, channel corridor migration at outer bends was typically approximately 20 to 40 m.

Reach 12 is considered typically laterally unstable due to the high level of floodplain reactivation.

Table 5: Channel Bank Delineation and Comparison

Reach	Representative Subreach (km)	Description
Reach 1 (Red Deer River)—Dickson Dam to STN 13+000	1-6	■ Historic planform is wandering with narrow, single-threaded sub-sections ~150-200 m in width punctuated by wider channel corridors up to 700 m wide containing vegetated islands ■ Following construction of Dickson Dam, valley has become submerged up to a width of approximately 2,000 m ■ Subreach is considered laterally stable
Reach 2 (Red Deer River)—STN 13+000 to STN 23+600	14-20	■ Wandering planform with a wide (approximately 250 m) active channel corridor and abundant minor sub-dominant channels ■ Downstream end of left bank is confined by bluffs ■ Abundant vegetated islands ■ Emergence of new sub-dominant channels resulted in up to 300 m of localized widening on the upstream half of the left bank ■ Limited narrowing (<100 m) on the upstream end the left bank due to abandonment of sub-dominant channels ■ Dominant and sub-dominant channels migrated extensively within the channel corridor with channel movement up to 300 m ■ Subreach is considered laterally unstable

Table 5: Channel Bank Delineation and Comparison

Reach	Representative Subreach (km)	Description
Reach 3 (Red Deer River)—STN 23+600 to James River confluence	28-33	■ Wandering to braided planform with a wide (typically greater than 800 m) channel corridor ■ Floodplain is unconfined ■ Abundant vegetated islands ■ Channel corridor has widened to both the left and right over most of the sub-reach; widening is greatest on the left bank, where the active channel moved to the northwest almost 600 m ■ The dominant channel shifted up to approximately 1,000 m from the right to the left edge of the channel corridor ■ The modern channel corridor appears to contain fewer vegetated islands than during the historic period ■ Subreach is considered laterally unstable
	39-41	■ Typically braided planform ■ Channel corridor is confined on the left bank by bluffs ■ Channel corridor contains a few large vegetated islands ■ Bank alignment over most of the reach is typically stable, but there is localized movement of the right bank up to approximately 150 m due to sub-dominant channel abandonment and migration ■ Dominant and sub-dominant channels have migrated up to approximately 120 m within the channel corridor ■ The general orientation of the dominant channel has remained relatively consistent (though it has migrated) ■ Subreach is considered laterally unstable
Reach 4 (Red Deer River)—James River confluence to Bearberry Creek confluence	49-54	■ Braided planform ■ Channel corridor is confined by bluffs on the downstream half of the left bank ■ Channel corridor contains several large vegetated islands ■ Left bank has moved to the left in localized areas (up to approximately 80 m) and to the right (up to approximately 120 m) due to sub-dominant channel migration and abandonment ■ Right bank has moved to the left up to approximately 750 m due to the abandonment of a sub-dominant channel ■ The active channel shifted to the east approximately 215 m and has widened by up to approximately 180 m ■ Subreach is considered laterally unstable
	57-59	■ Planform is braided ■ Upstream end of the channel corridor is laterally constrained near the bridge at Highway 27 but widens in the downstream direction ■ The majority of vegetated islands were scoured away ■ Channel corridor has typically narrowed by up to approximately 200 m ■ Approximately 1 kilometre downstream of the Highway 27 bridge, the channel corridor has migrated approximately 100 m to the east ■ Subreach is considered laterally unstable

Table 5: Channel Bank Delineation and Comparison

Reach	Representative Subreach (km)	Description
Reach 5 (Red Deer River)—Bearberry Creek confluence to Bearberry Prairie Natural Area	59-60	■ Wandering to braided planform ■ Channel is confined near the Highway 27 bridge ■ The majority of vegetated islands were scoured away ■ Planform becomes more braided in the modern period ■ Channel corridor has shifted to the west approximately 50 m ■ New sub-dominant channel has formed on the right side of the channel corridor approximately 350 m upstream of the Highway 27 bridge ■ Development is encroaching onto the floodplain; bank protection is present on the left bank. Bank protection on the right bank is sporadic ■ The dominant channel has moved from the right to the left side of the corridor upstream of the bridge and from the left to the right under the bridge ■ Subreach is considered laterally unstable
	67-71 (southern fork)	■ Wandering planform with localized braiding ■ The channel corridor is constrained by bluffs on the right bank at the downstream end of the subreach ■ Several vegetated islands present ■ Right bank migrates to the right (south) up to 200 ■ Avulsion and migration of the dominant channel occur throughout the subreach. Channel displacement is in the order of 100 m ■ Subreach is considered laterally unstable
	66-70 (northern fork)	■ In the historical period, the channel corridor had a wandering planform, and the active channel was composed of three primary branches separated by large vegetated islands ■ Most of the flow has been diverted away from the subreach and the channel has mostly become vegetated; however, a defined channel emerges downstream of the subreach ■ Subreach is considered laterally unstable
Reach 6 (Red Deer River)—Bearberry Prairie Natural Area to STN 85+600	72-77	■ Wandering planform with localized braiding ■ Active channel has become more single-threaded in the modern period ■ The downstream end of the subreach is confined by bluffs along the right bank ■ Abundant vegetated islands present ■ Channel corridor has shifted to the left (north) approximately 140 m in the upstream portion of the sub-reach and has narrowed approximately 200 m locally due to the abandonment of a sub-dominant channel ■ The dominant channel has typically migrated in the order of 100-300 m throughout the sub-reach ■ Subreach is considered laterally unstable

Table 5: Channel Bank Delineation and Comparison

Reach	Representative Subreach (km)	Description
Reach 7 (Bearberry Creek)—Red Deer River confluence to Bearberry Creek weir	0.30-1.2	■ Straight to meandering planform with frequent small bars and islands ■ Banks are protected with engineered works and are similarly aligned in both the historic and modern period ■ Channel corridor has been straightened ■ Locations of mid-channel bars have typically shifted and become vegetated ■ Subreach is considered laterally stable
Reach 8 (Bearberry Creek)—Bearberry Creek weir to upstream end of fish passage	1.4-1.7	■ Channel corridor was sinuous during the historical period ■ Flow appears to have been diverted into a straightened channel to the northeast of the historic channel alignment ■ A fish passage was constructed to the north in the vicinity of the historic channel alignment ■ Banks are protected with engineered works ■ No apparent bars or islands present ■ Subreach is considered laterally stable
Reach 9 (Bearberry Creek)—Upstream end of fish passage to Cowboy Trail	1.7-2.2	■ Single-threaded planform ■ Channel corridor was highly sinuous during the historical period and was straightened prior to the modern period ■ No observed bank protection; channel corridor is unconfined ■ No apparent bars or islands present ■ Subreach is considered laterally unstable
Reach 10 (Bearberry Creek)—Cowboy Trail to STN 13+300	6.7-8.0	■ Typically single-threaded, torturous meandering planform ■ Channel corridor is unconfined ■ Occasional islands present ■ Channel corridor has migrated approximately 20-30 m at outer bends ■ Channel corridor width has remained approximately consistent between the historical and modern periods ■ Subreach is considered laterally unstable
	8.6-10	■ Typically single-threaded, torturous meandering planform ■ Occasional islands and side bars present ■ Channel corridor is unconfined ■ Channel corridor bends have been cut off in two locations abandoning approximately 400 and 650 metres of channel, respectively; cut-off of one of the ~400 m bends had begun at the time the historical photos were taken ■ Channel corridor migration on the outer bends is typically ~5-35 m, with one bend migrating approximately 100 metres ■ Subreach is considered laterally unstable
Reach 11 (Bearberry Creek)—STN 13,300 to STN 14+200	13-14	■ Planform is meandering with a low sinuosity ■ No apparent bars or islands present ■ Channel corridor is unconfined ■ Bank alignment has remained approximately stable between the historical and modern periods ■ Subreach is considered laterally stable

Table 5: Channel Bank Delineation and Comparison

Reach	Representative Subreach (km)	Description
Reach 12 (Bearberry Creek)—STN 14+200 to STN 17+100	15-16	■ Single-threaded, torturous meandering planform ■ Rare small side bars present ■ Channel corridor is unconfined ■ Channel corridor bend has been cut off, abandoning approximately 100 m of channel ■ Channel corridor has migrated approximately 10 m on outer bend ■ Subreach is considered laterally unstable
	16-17	■ Single-threaded, torturous meandering planform ■ Rare small mid-channel and side bars ■ Channel corridor is unconfined ■ Channel corridor bends have been cut off in two locations abandoning approximately 300 m and 770 m of channel, respectively ■ Channel corridor migration on outer bends of typically ~20-40 m ■ Subreach is considered laterally unstable

LEGEND

- RIVER STATION POST (km)
- FLOW DIRECTION
- RIGHT BANK (2018)
- RIGHT BANK HISTORICAL (1962/1963)
- LEFT BANK (2018)
- LEFT BANK HISTORICAL (1962/1963)
- PROTECTED BANK (2018)
- PROTECTED BANK (1962/1963)
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- VEGETATED ISLAND HISTORICAL (1962/1963)

LEGEND KEY MAP

- STABLE SUBREACH

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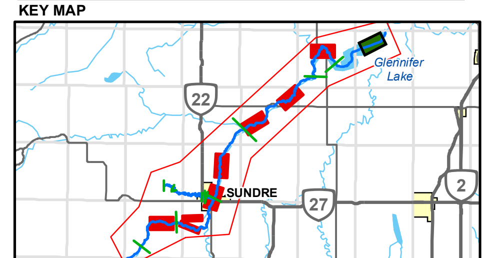
KEY MAP



PROJECT

UPPER RED DEER RIVER HAZARD STUDY

TITLE

CHANNEL BANK COMPARISON OF REACH 1 - UPPER RED DEER RIVER FROM DICKSON DAM TO STN 13+000 - REPRESENTATIVE SUBREACH

REFERENCE(S)

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DESIGNED	MT
PREPARED	SK
REVIEWED	RA
APPROVED	WP

PROJECT NO.	CONTROL	REV.	FIGURE
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LEGEND

- RIVER STATION POST (km)
- FLOW DIRECTION
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- RIGHT BANK HISTORICAL (1962/1963)
- LEFT BANK (2018)
- LEFT BANK HISTORICAL (1962/1963)
- PROTECTED BANK (2018)
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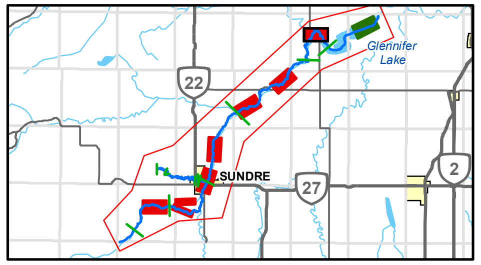
LEGEND KEY MAP

- UNSTABLE SUBREACH

KEY MAP



PROJECT
UPPER RED DEER RIVER HAZARD STUDY

TITLE
CHANNEL BANK COMPARISON OF REACH 2 - UPPER RED DEER RIVER FROM STN 13+000 TO STN 23+600 - REPRESENTATIVE SUBREACH

REFERENCE(S)
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APPROVED	WP

PROJECT NO.	CONTROL	REV.	FIGURE
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Classification: Public

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LEGEND KEY MAP

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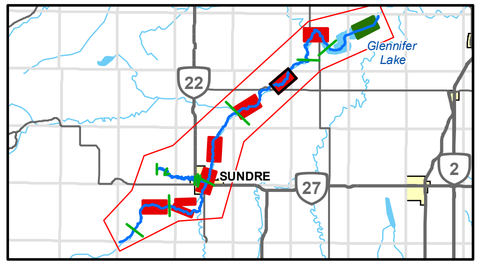

PROJECT

UPPER RED DEER RIVER HAZARD STUDY

TITLE

CHANNEL BANK COMPARISON OF REACH 3 - UPPER RED DEER RIVER FROM STN 23+600 TO JAMES RIVER CONFLUENCE - REPRESENTATIVE SUBREACH 1 OF 2

REFERENCE(S)

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DESIGNED	MT
PREPARED	SK
REVIEWED	RA
APPROVED	WP

PROJECT NO.	CONTROL	REV.	FIGURE
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Classification: Public

LEGEND

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LEGEND KEY MAP

- UNSTABLE SUBREACH

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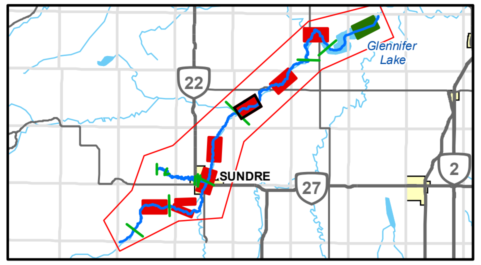

PROJECT

UPPER RED DEER RIVER HAZARD STUDY

TITLE

CHANNEL BANK COMPARISON OF REACH 3 - UPPER RED DEER RIVER FROM STN 23+600 TO JAMES RIVER CONFLUENCE - REPRESENTATIVE SUBREACH 2 OF 2

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PROJECT NO.	CONTROL	REV.	FIGURE
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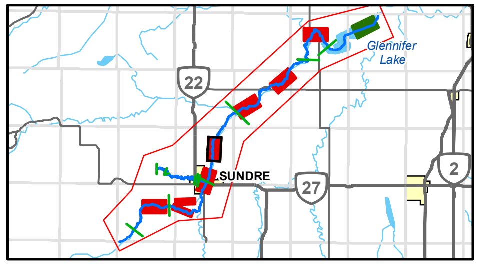

LEGEND
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- PROTECTED BANK (2018)
- PROTECTED BANK (1962/1963)
- VEGETATED ISLAND (2018)
- VEGETATED ISLAND HISTORICAL (1962/1963)

LEGEND KEY MAP
- UNSTABLE SUBREACH

0 400 800
1:10,000 METRES

PROJECT
UPPER RED DEER RIVER HAZARD STUDY

TITLE
CHANNEL BANK COMPARISON OF REACH 4 - UPPER RED DEER RIVER FROM JAMES RIVER CONFLUENCE TO BEARBERRY CREEK CONFLUENCE - REPRESENTATIVE SUBREACH 1 OF 2

REFERENCE(S)
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ALBERTA ENVIRONMENT AND PARKS

Alberta Government

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APPROVED	WP

PROJECT NO.	CONTROL	REV.	FIGURE
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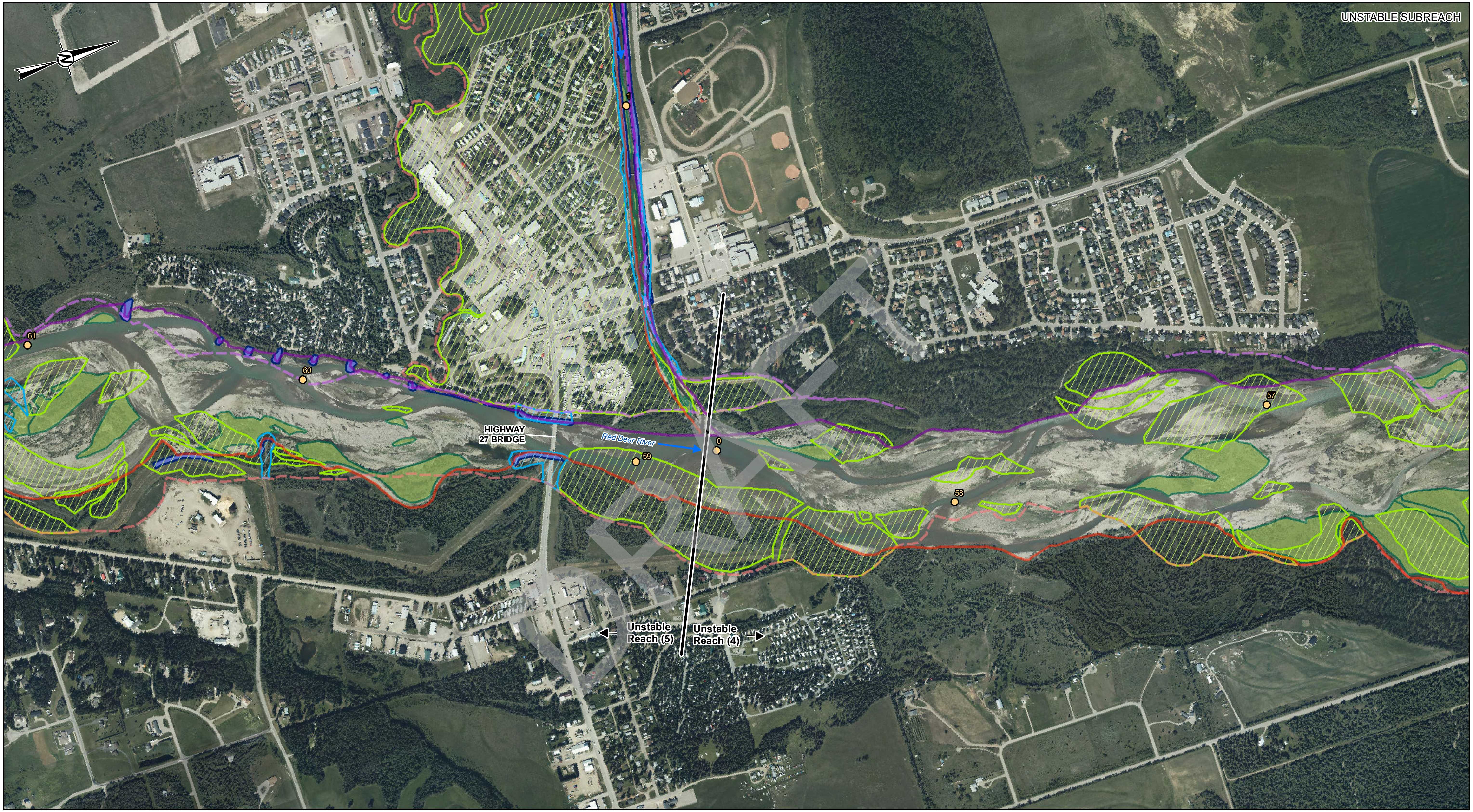

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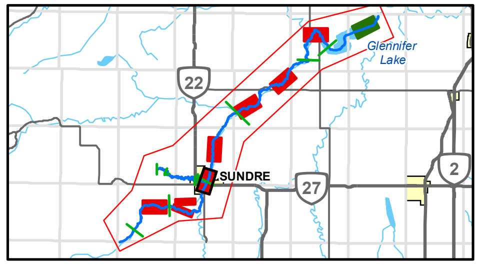
LEGEND KEY MAP

- UNSTABLE SUBREACH

KEY MAP



PROJECT

UPPER RED DEER RIVER HAZARD STUDY

TITLE

CHANNEL BANK COMPARISON OF REACHES 4 AND 5 - UPPER RED DEER RIVER IN THE VICINITY OF SUNDRE - REACH 4 REPRESENTATIVE SUBREACH 2 OF 2 AND REACH 5 REPRESENTATIVE SUBREACH 1 OF 3

REFERENCE(S)

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PROJECT NO.	CONTROL	REV.	FIGURE
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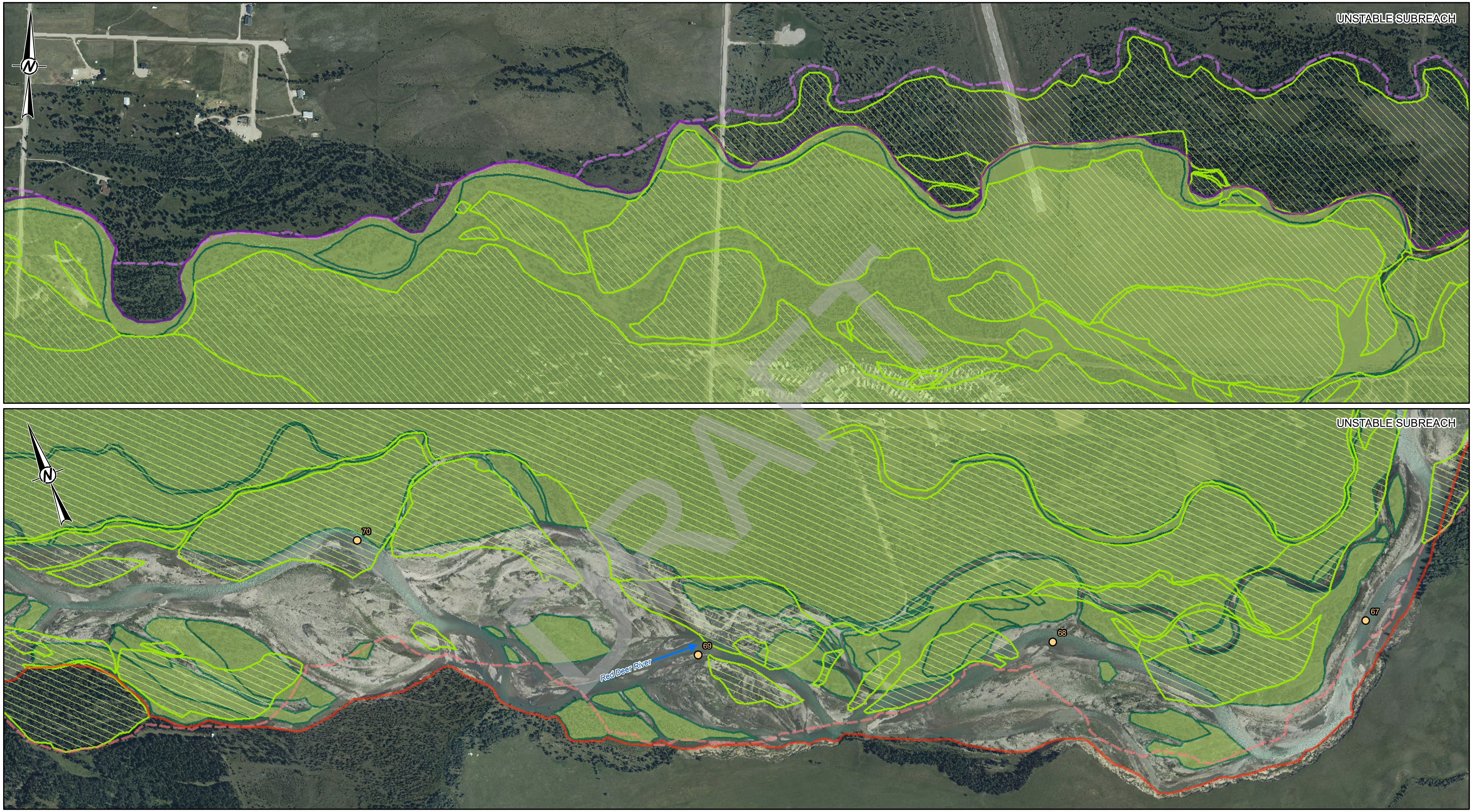

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- UNSTABLE SUBREACH

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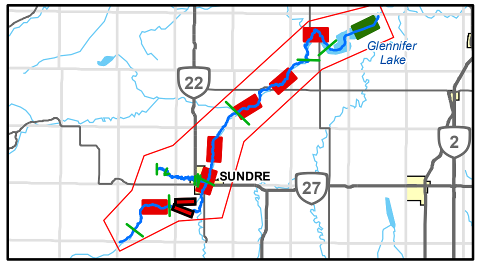
KEY MAP



PROJECT

UPPER RED DEER RIVER HAZARD STUDY

TITLE

CHANNEL BANK COMPARISON OF REACH 5 - UPPER RED DEER RIVER FROM BEARBERRY CREEK CONFLUENCE TO BEARBERRY PRAIRIE NATURAL AREA - REPRESENTATIVE SUBREACHES 2 AND 3 OF 3

REFERENCE(S)

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PROJECT NO.	CONTROL	REV.	FIGURE
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Classification: Public

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LEGEND KEY MAP

- UNSTABLE SUBREACH

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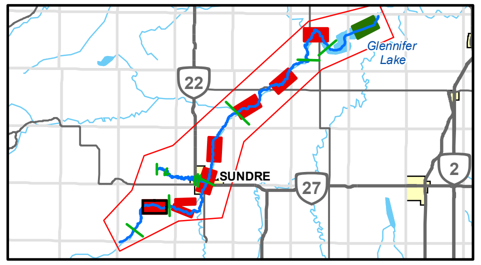
KEY MAP



PROJECT

UPPER RED DEER RIVER HAZARD STUDY

TITLE

CHANNEL BANK COMPARISON OF REACH 6 - BEARBERRY PRAIRIE NATURAL AREA TO STN 85+600 - REPRESENTATIVE SUBREACH

REFERENCE(S)

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PROJECT NO.	CONTROL	REV.	FIGURE
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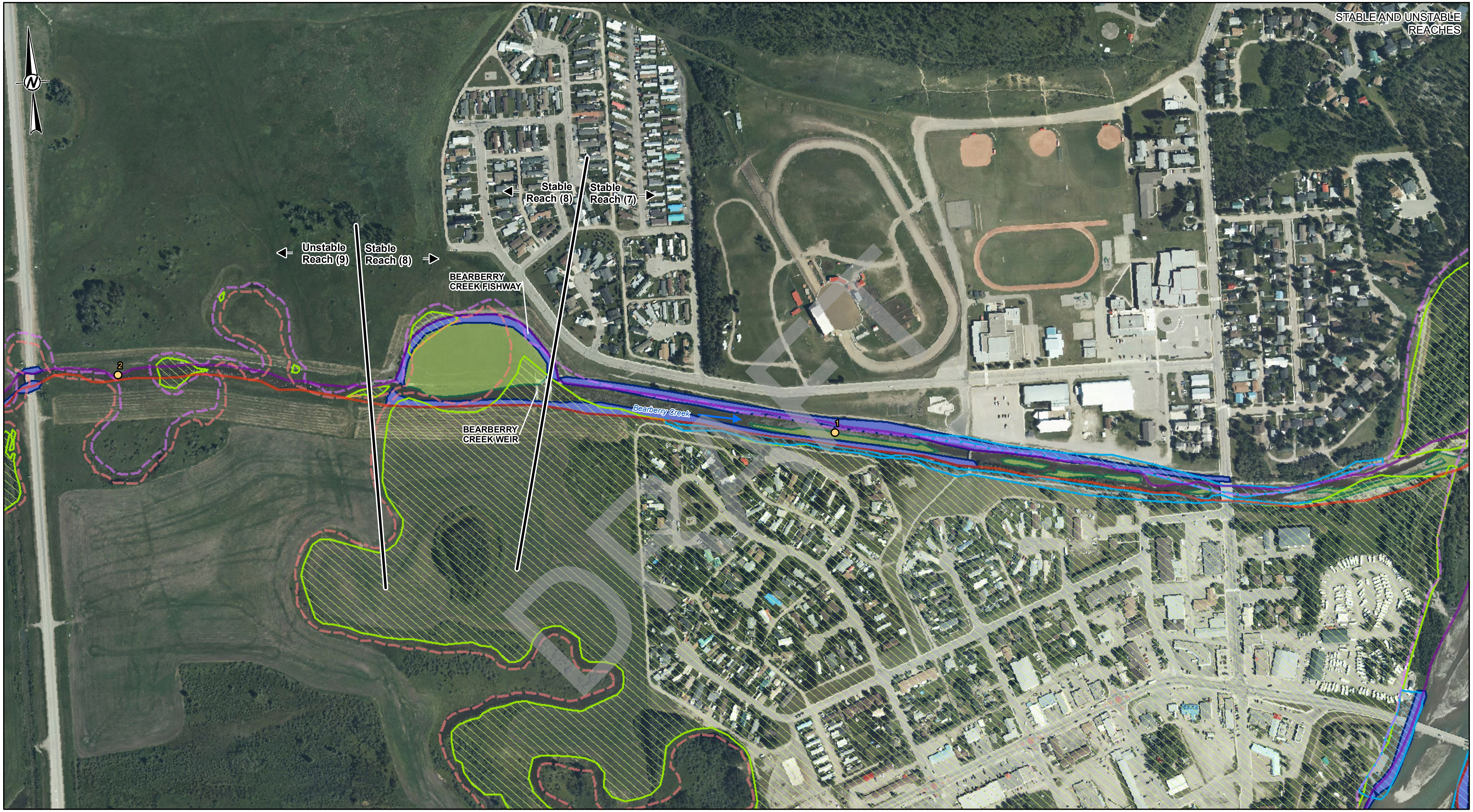

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- PROTECTED BANK (1962/1963)
- VEGETATED ISLAND (2018)
- VEGETATED ISLAND HISTORICAL (1962/1963)

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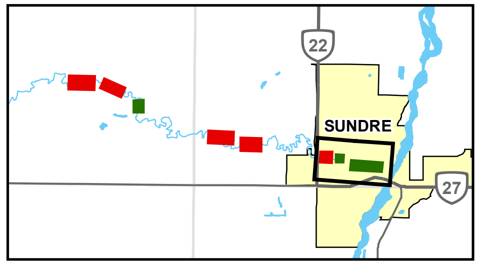
1:5,000 METRES

LEGEND KEY MAP

- STABLE REACH/SUBREACH
- UNSTABLE REACH/SUBREACH

KEY MAP



PROJECT
UPPER RED DEER RIVER HAZARD STUDY

TITLE
CHANNEL BANK COMPARISON OF REACHES 7, 8, AND 9 - BEARBERRY CREEK IN THE VICINITY OF SUNDRE

REFERENCE(S)
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PROJECT NO.	CONTROL	REV.	FIGURE
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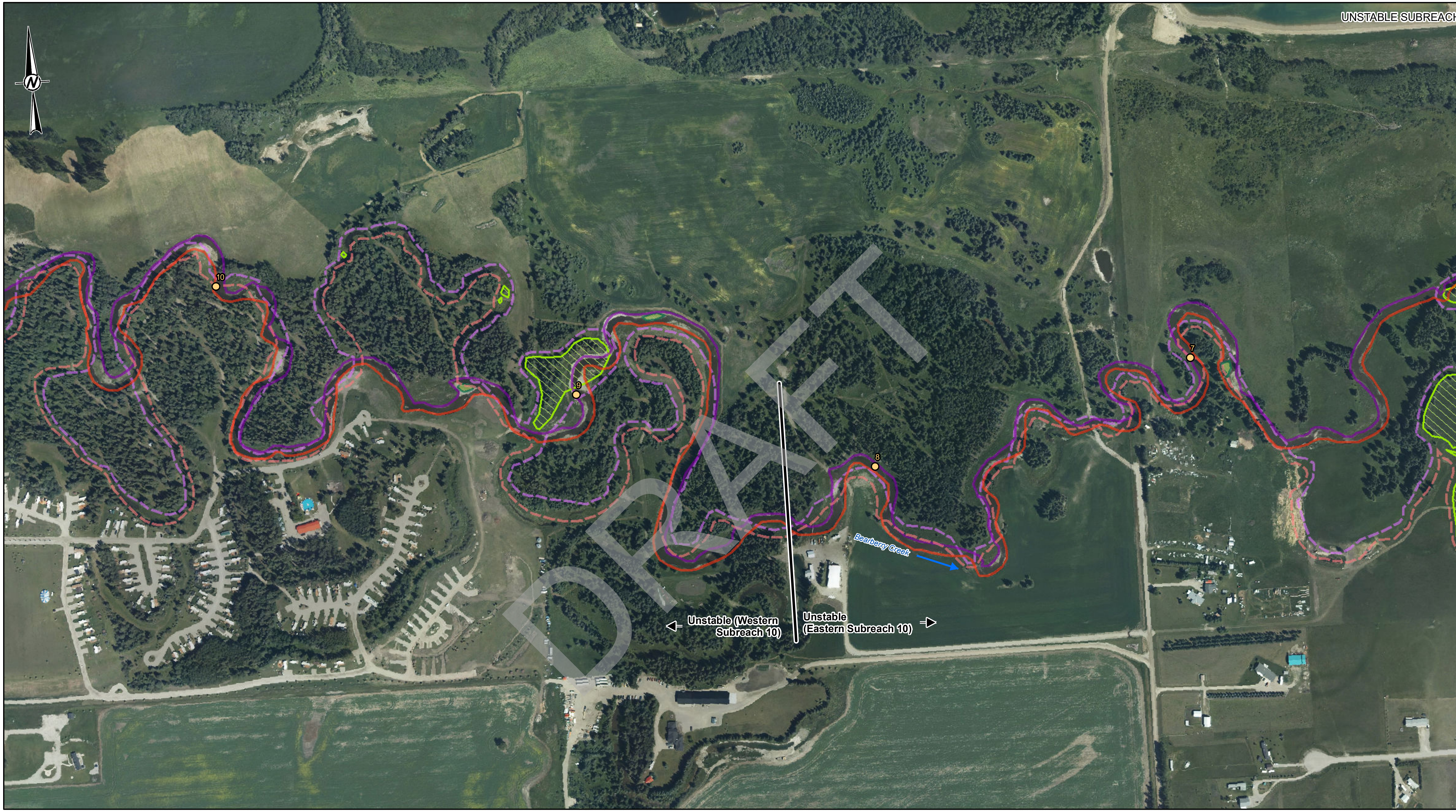

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- PROTECTED BANK (1962/1963)
- VEGETATED ISLAND (2018)
- VEGETATED ISLAND HISTORICAL (1962/1963)

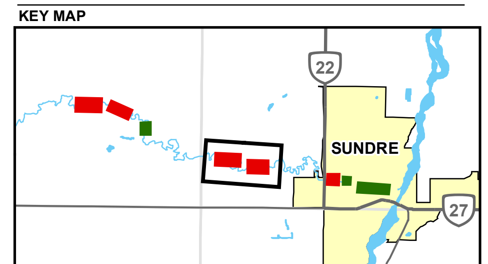
0 200 400

1:5,000 METRES

LEGEND KEY MAP

- STABLE REACH/SUBREACH
- UNSTABLE REACH/SUBREACH

KEY MAP



PROJECT

UPPER RED DEER RIVER HAZARD STUDY

TITLE

CHANNEL BANK COMPARISON OF REACH 10 - BEARBERRY CREEK FROM COWBOY TRAIL TO STN 13+300 - REPRESENTATIVE SUBREACHES

REFERENCE(S)

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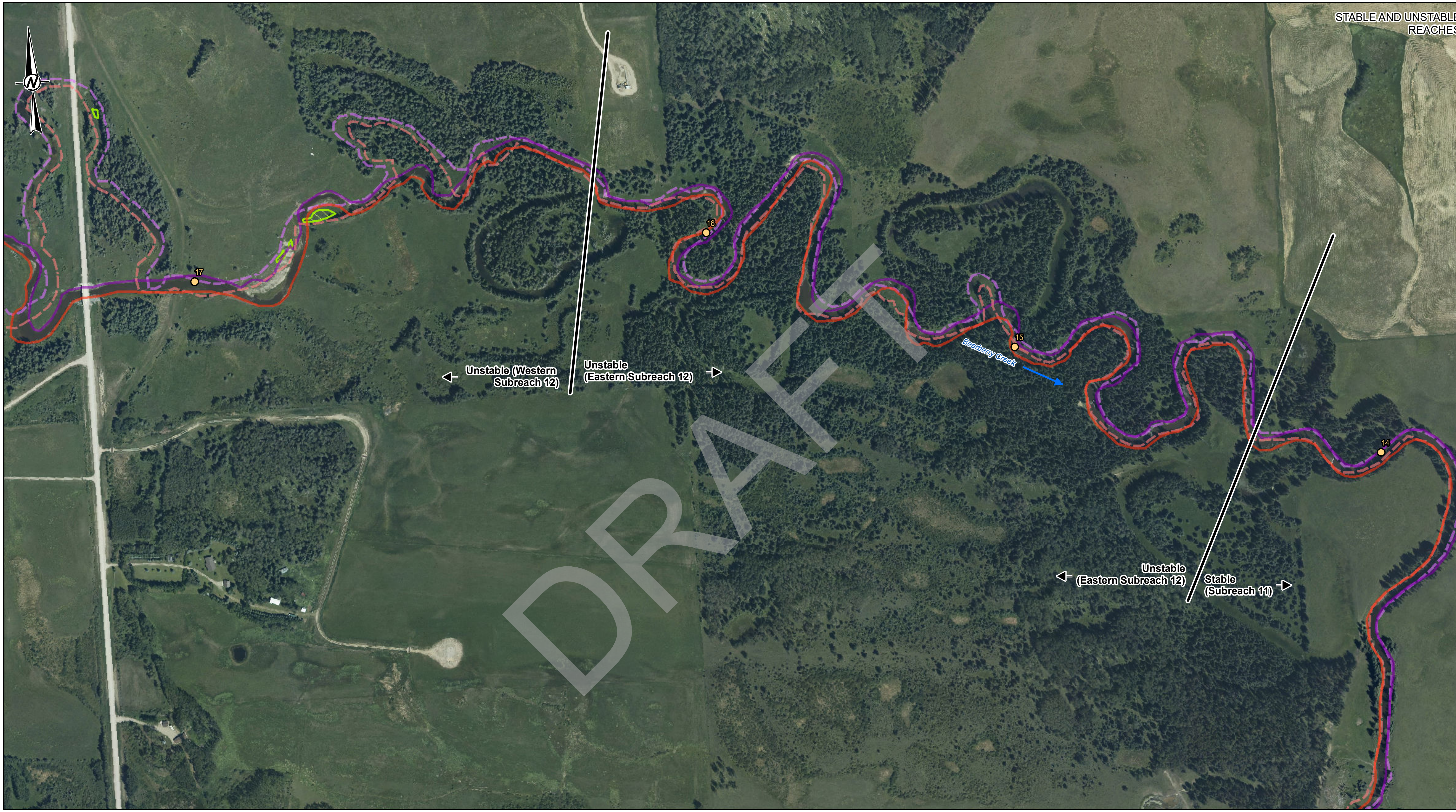

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- VEGETATED ISLAND (2018)
- VEGETATED ISLAND HISTORICAL (1962/1963)

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1:5,000 METRES

LEGEND KEY MAP

- STABLE REACH/SUBREACH
- UNSTABLE REACH/SUBREACH

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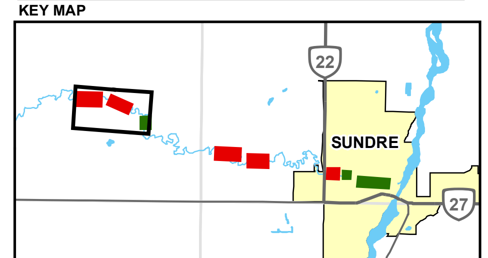

PROJECT
UPPER RED DEER RIVER HAZARD STUDY

TITLE
CHANNEL BANK COMPARISON OF REACHES 11 AND 12 - BEARBERRY CREEK UPSTREAM OF STN 14+200

REFERENCE(S)
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REVIEWED	RA
APPROVED	WP

PROJECT NO.	CONTROL	REV.	FIGURE
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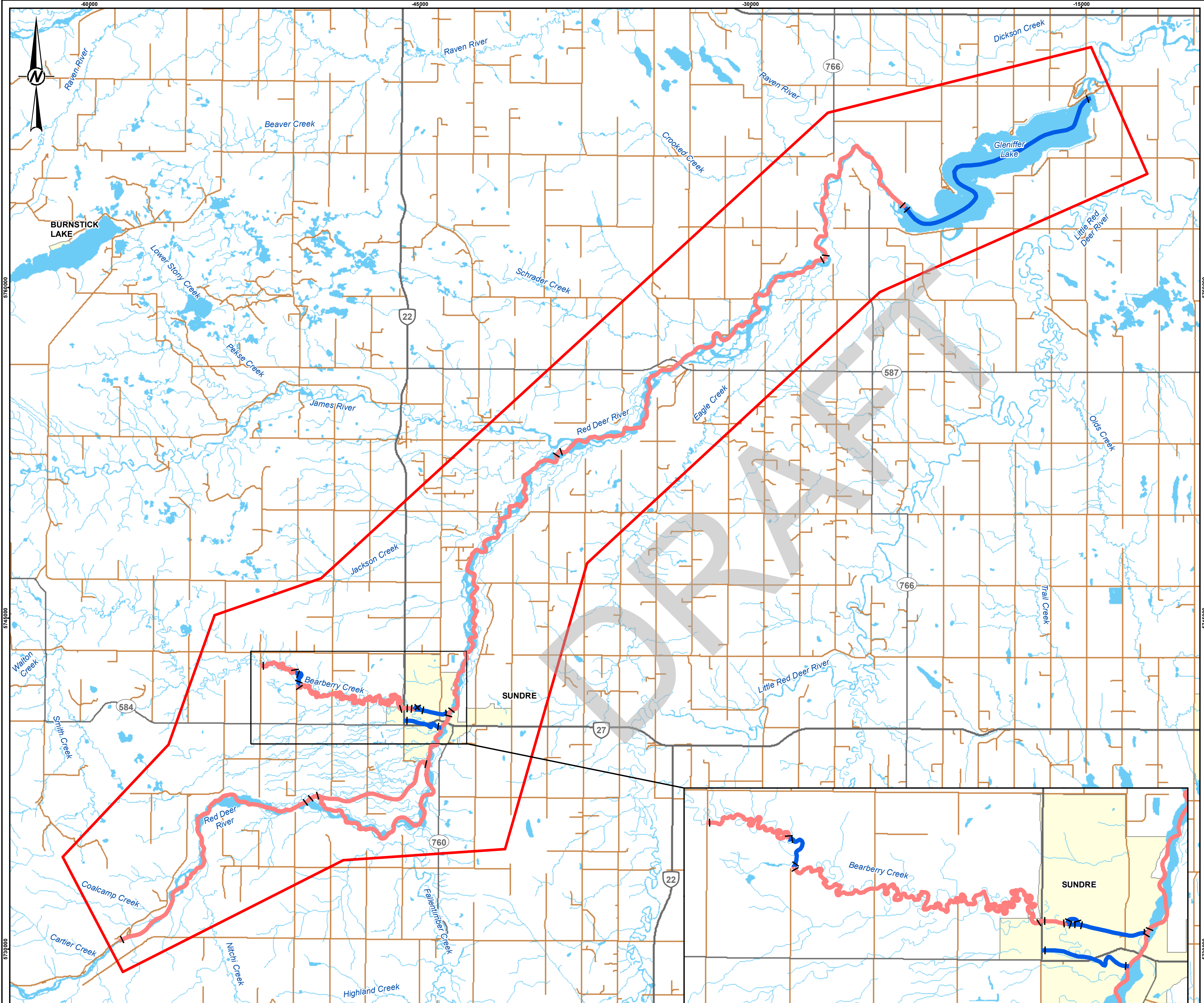

LEGEND

PRIMARY HIGHWAY
SECONDARY HIGHWAY
LOCAL ROAD
WATERCOURSE
WATERBODY
POPULATED PLACE
RIVER HAZARD STUDY AREA

RIVER REACH

STABLE
UNSTABLE

0 4 8
1:175,000 METRES

REFERENCE(S)

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CLIENT
ALBERTA ENVIRONMENT AND PARKS

PROJECT
UPPER RED DEER RIVER HAZARD STUDY

TITLE
CHANNEL STABILITY OVERVIEW MAP

CONSULTANT
GOLDER

YYYY-MM-DD	2019-07-23
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APPROVED	WP

PROJECT NO.	CONTROL	REV.	FIGURE
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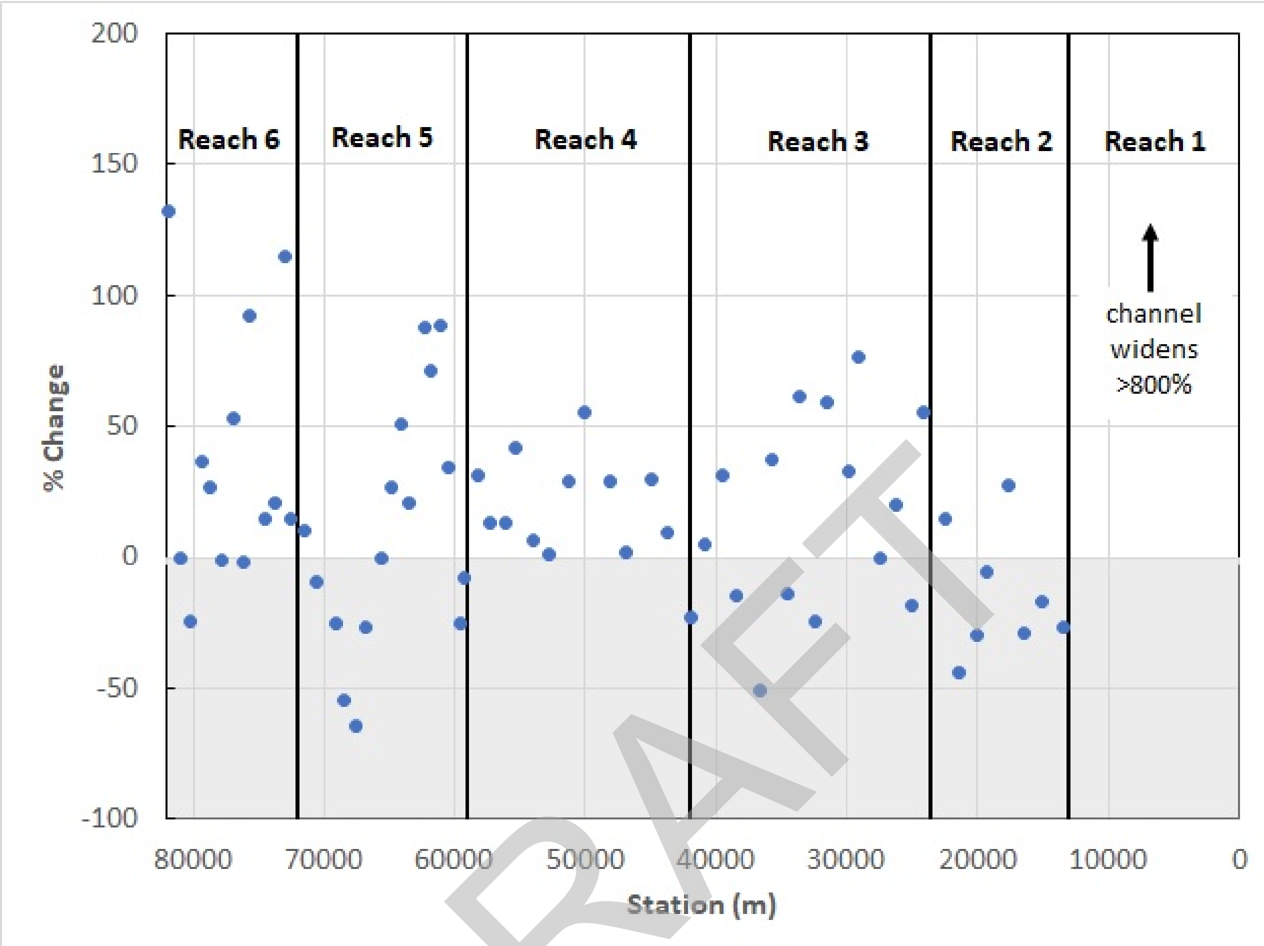

Figure 15: Change in active channel width on Upper Red Deer River, early 1960s-2018. The active channel width is defined as the sum of all portions of the channel that are not fully vegetated.

4.3 Cross Section Comparison

Detailed qualitative and quantitative descriptions and figures for the cross section comparison are presented in Appendix A. Due to limited availability of historical data, comparisons were only available for the upstream 4 km of Reach 4, the downstream kilometre of Reach 5, Reaches 7, 8, and 9, and the downstream kilometre of Reach 10. Table 6 provides a summary of representative cross section geometry. Statistical checks for significant differences between historical and recent cross section metrics were not performed because of the low number of cross sections suitable for comparison.

Two types of behaviour were identified in the sections of Reach 4 (Red Deer River – James River confluence to Bearberry Creek confluence) where cross section comparison was possible. The dominant and sub-dominant channels between river kilometres 55 and 58 typically became shallower by approximately 0.6 m and narrower by approximately 10 m. This has resulted in a slightly lower bankfull cross sectional area. Conversely, the cross sectional area in the upstream kilometre of Reach 4 (just downstream of the confluence with Bearberry Creek) has increased by approximately 50 m^2. The bankfull width and maximum depth both decreased, but the average channel depth increased because the channel geometry evolved from a skewed profile dominated by a deep, relatively narrow area near the thalweg to a more rectangular shape with a smaller distribution of depths (see Appendix A).

The bankfull cross sectional area of the downstream kilometre of Reach 5 (Red Deer River – Bearberry Creek confluence to Bearberry Prairie Natural Area) decreased by approximately 110 m^2 due primarily to a reduction in channel width of approximately 100 m.

The bankfull cross sectional area of Reach 7 (Bearberry Creek – Red Deer River confluence to Bearberry Creek weir) was approximately stable between the historical and recent periods. The channel width increased by a few metres, but this was offset by a slight decrease in average channel depth. The maximum bankfull depth increased by approximately 0.4 m as the channel scoured into its bed and developed a more skewed profile (see Appendix A).

In Reach 8 (Bearberry Creek – Bearberry Creek weir to upstream end of fish passage), the channel geometry evolved from being approximately trapezoidal to developing a more skewed cross sectional shape characterized by a bar adjacent to a narrow area near the thalweg (see Appendix A). This resulted in an increase of the maximum bankfull depth of approximately 1.4 metres, a widening of the channel by approximately 5 m, and a small increase in channel area. The average depth remained approximately consistent.

Over the observed period, the bankfull cross sectional area of Reach 9 (Bearberry Creek – upstream end of fish passage to Cowboy Trail) decreased by approximately 12 m^2. Bankfull width and depth remained approximately consistent, and the cause of the reduction in channel capacity appears to be associated with the growth of a small bar on the left bank (see Appendix A).

Channel cross sectional geometry appears to have changed little in Reach 10 (Bearberry Creek – Cowboy Trail to STN 13+300).

Table 6: Summary of Representative Cross Section Geometry

Reach or Representative Subreach	Maximum Bankfull Depth (m)		Average Bankfull Depth (m)		Bankfull Width (m)		Cross sectional Area (m^2)	
	Historical	Recent	Historical	Recent	Historical	Recent	Historical	Recent
Reach 4—Red Deer River (kms 55-58)	2.1	1.7	0.66	0.60	290	280	180	170
Reach 4—Red Deer River (km 59)	3.2	1.6	0.46	0.80	270	210	120	170
Reach 5—Red Deer River (km 60-61)	2.1	2.3	1.0	1.1	240	140	240	130
Reach 7—Bearberry Creek	3.8	4.2	2.5	2.4	50	53	130	130
Reach 8—Bearberry Creek	2.8	4.2	2.0	1.9	35	40	70	77
Reach 9—Bearberry Creek	3.6	3.4	2.3	2.0	38	39	86	78
Reach 10—Bearberry Creek	1.7	1.8	1.4	1.1	14	18	19	19

4.4 Thalweg Profile Comparison

Observations on channel longitudinal profile and thalweg elevation changes over time were made on the Red Deer River and Bearberry Creek using the 1992 and 2017 surveys (Figure 16 and Figure 17). Elevation difference plots were created to highlight the measured changes and are presented in Figure 18 and Figure 19. Positive numbers are indicative of accretion (or aggradation) and negative numbers are indicative of scour (or degradation). Table 7 summarizes reach-averaged channel slopes and net fluxes of sediment through the reaches. Historical thalweg data is not available for Reaches 1, 2, 3, 6, 11, and 12. Only partial coverage of Reaches 4, 5, and 10 are available.

Longitudinal profiles exhibiting a concave shape are typical of a stream reach in equilibrium (Ritter et al., 1995). The longitudinal profile for the Upper Red Deer River (Figure 16) exhibits an approximately concave profile with the exception of Reaches 4 and 5, where the profile is slightly convex. The Bearberry Creek longitudinal profile (Figure 17) is convex, which suggests that the river is generally out of equilibrium. More details on each river are provided below.

4.4.1 Red Deer River

The Red Deer River originates in the Rocky Mountains and enters the Prairies not far upstream of Reach 6. In the study area, the terrain surrounding the river is transitioning from relatively steep alpine topography to gentler conditions. The land surface in the region may also be sinking by up to a few millimetres per year due to rebound of the continental crust following the last ice age (Snay et al., 2016). The channel gradient is approximately 0.0050 in Reach 6, and in general it becomes shallower in the downstream direction.

There is a discontinuity in the longitudinal profile in Reaches 4 and 5. The gradient in Reach 4 (approximately 0.0036) is slightly greater than the gradient in Reach 5 (approximately 0.0034), and the bed elevation is not stable over the observed period. Reach 5 is characterized by degradation; over the downstream ~4 km of the reach, the thalweg has lowered up to 2 metres (Figure 18) and the reach has experienced a net loss of over 2,000 m^3 of sediment per unit channel width (Table 7). The cause of the degradation is not apparent; however, one possibility is that the ability of the river to transport sediment has increased. Since the partial abandonment of the northern fork of the Red Deer in Reach 5 over the observed period (see Section 4.2.5), the southern fork will have received a greater proportion of flow, which may have increased the overall stream power in the reach. The rate of sediment transport is typically proportional to stream power.

Reach 4 has accumulated just under 1,000 m^3 of sediment per unit channel width in river kilometres 54 to 59 over the observed period. Most sediment deposition has occurred in the first kilometre downstream of Bearberry Creek (Figure 18), where the thalweg elevation has risen approximately 1 metre over the observed period. Much of this sediment is likely sourced from Reach 5 as well as Bearberry Creek, which has also experienced a net loss of sediment over the observed period (see below). Degradation has occurred over river kilometres 56 to 58, likely because of the local increase in slope due to deposition upstream. The thalweg elevation has remained more stable over river kilometres 54 to 56.

Table 7: Summary of Net Volume Bed Change

River	Reach and Description	Assessed River Stations (km)	Average Reach Slope (m/m)	Net Bed Volume Change per unit channel width (m^3/m)
Red Deer River	Reach 4—James River confluence to Bearberry Creek confluence	54 - 59	0.0036	980
	Reach 5—Bearberry Creek confluence to Bearberry Prairie Natural Area	59 - 63	0.0034	-2440
			Total net bed volume change for Upper Red Deer River	*-1460*
Bearberry Creek	Reach 7—Red Deer River confluence to Bearberry Creek weir	0 - 1.4	0.0057	-1040
	Reach 8—Bearberry Creek weir to upstream end of fish passage	1.4 - 1.7	0.0028	-120
	Reach 9—Upstream end of fish passage to Cowboy Trail	1.7 - 2.1	0.0026	-210
	Reach 10—Cowboy Trail to STN 13+300	2.1 - 6.4	0.0023	-920
			Total net bed volume change for Bearberry Creek	*-2300*

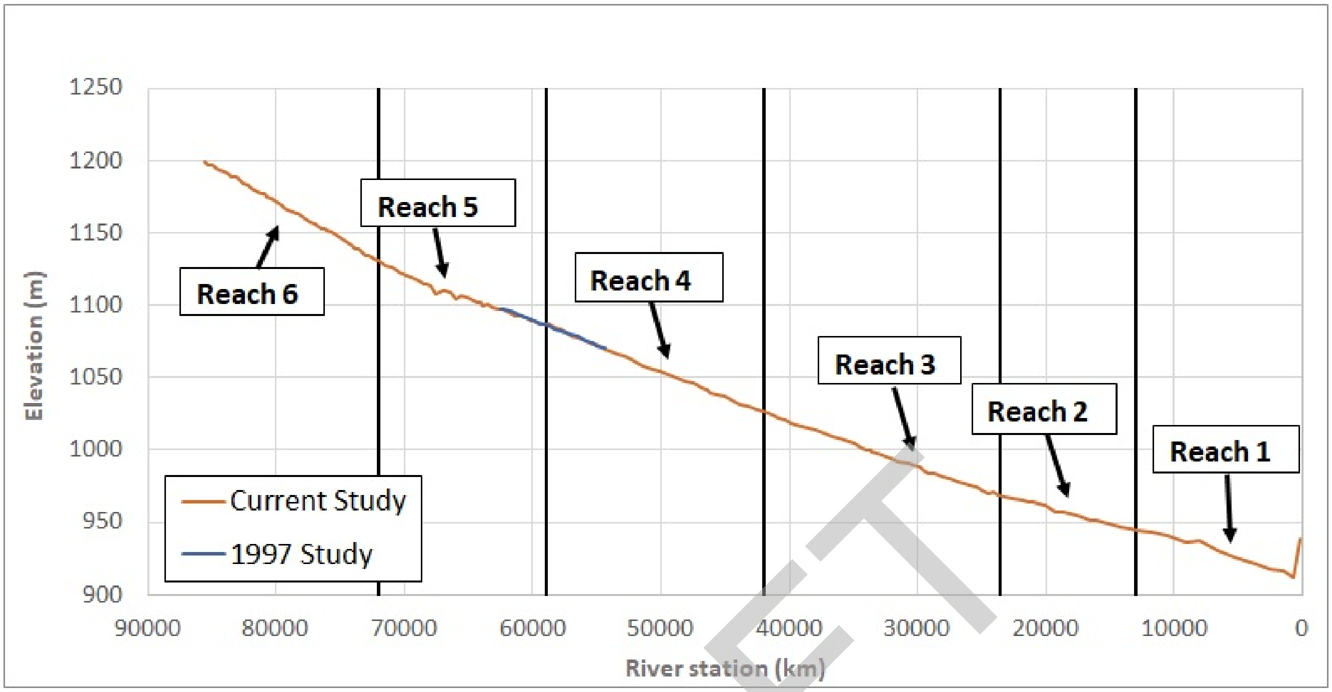

Figure 16: Longitudinal profile for Upper Red Deer River

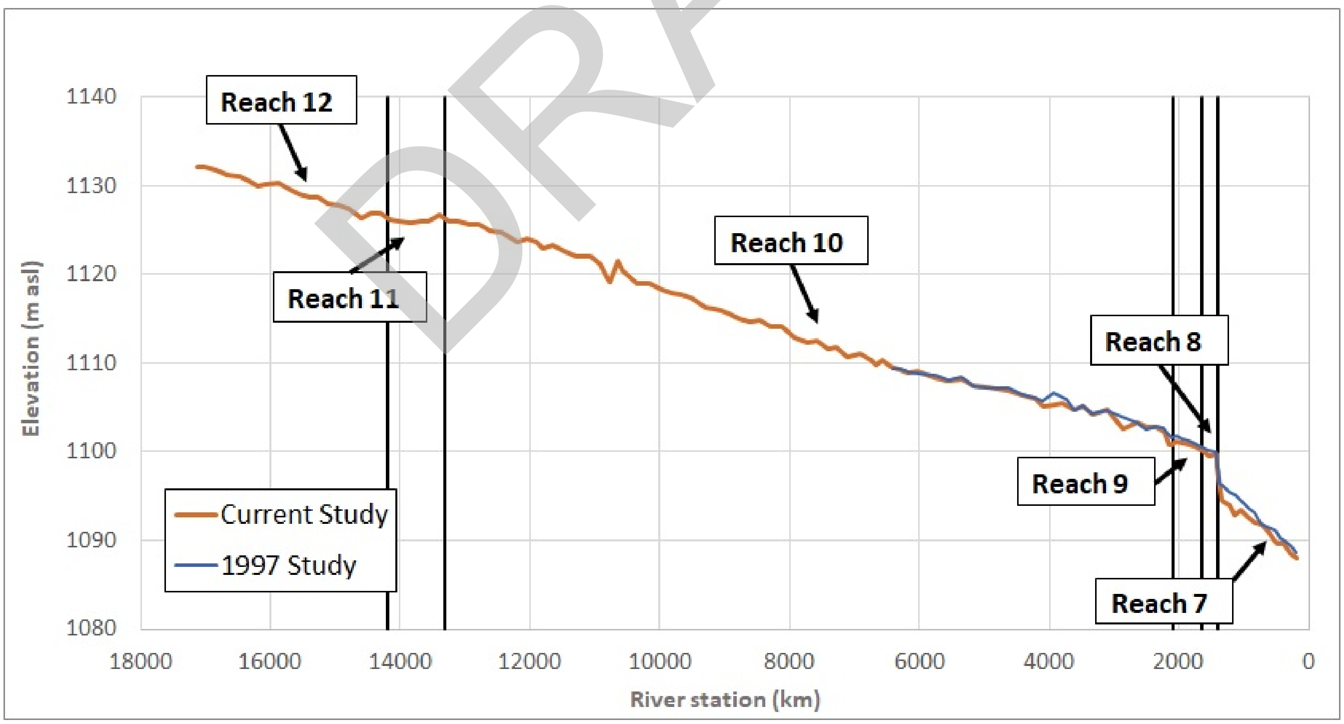

Figure 17: Longitudinal profile for Bearberry Creek

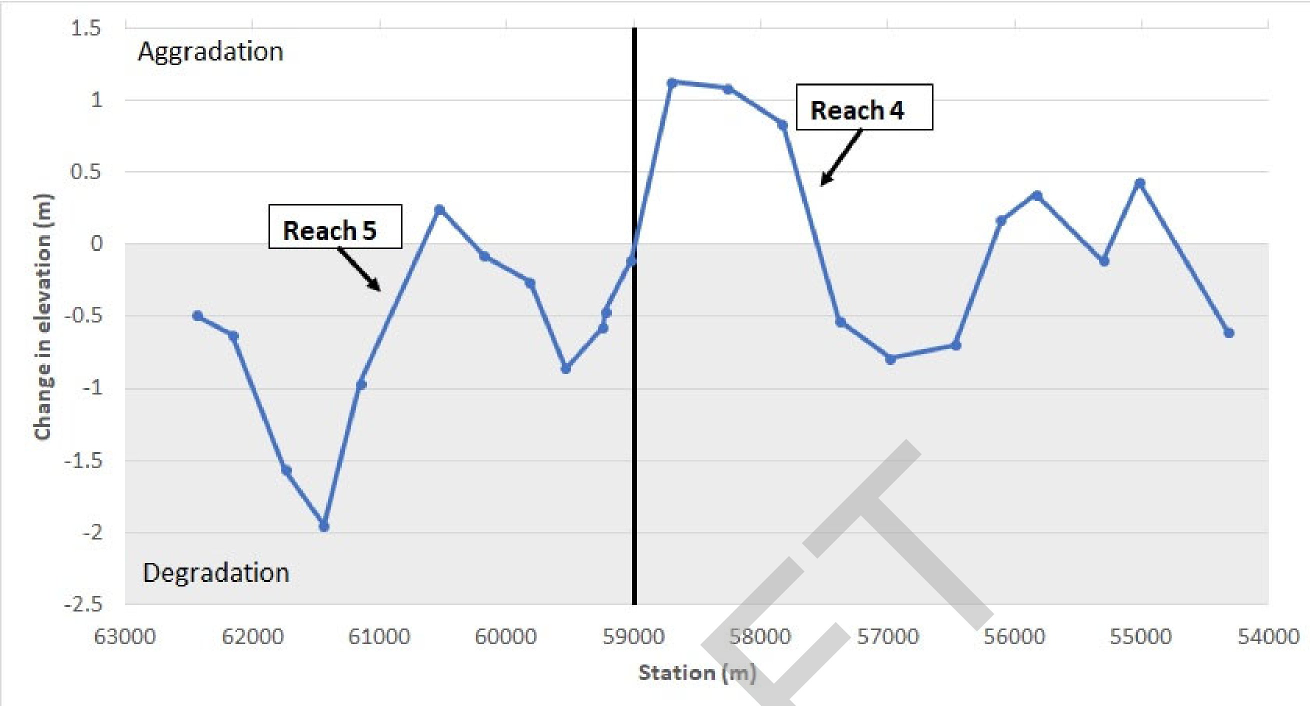

Figure 18: Upper Red Deer River thalweg elevation difference

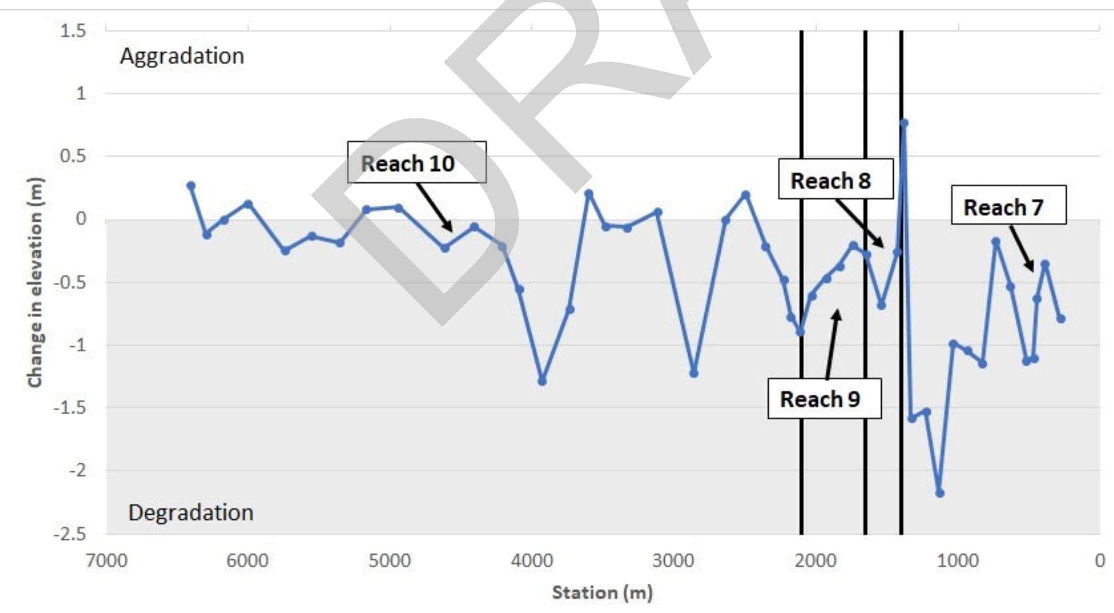

Figure 19: Bearberry Creek thalweg elevation difference

4.4.2 Bearberry Creek

Bearberry Creek flows through typically gentle terrain on the Prairies. In general, the gradient of Bearberry Creek increases in the downstream direction; it is approximately 0.0020 in Reach 12 and 0.0057 at the stream mouth. The exception is Reach 11, where the gradient locally flattens to approximately 0.00010 (Figure 17). Historical thalweg data is not available for this reach, so it is unclear whether the bed elevation is stable. The channel has not apparently migrated or experienced width change like surrounding Bearberry Creek reaches (see Section 4.2.11), so it is possible that there is a geologic control that defines the gradient and channel position.

Reaches 7, 8, and 9 are steeper than the upstream reaches. They have all been artificially straightened, and this typically results in gradient increases because the length of stream decreases while the total elevation change remains approximately the same. Net degradation has occurred in all three reaches over the observed period (Table 7, Figure 19) and has generally resulted in an overall lowering of the bed as well as the creation or deepening of pools (Figure 17). Reach 10 has experienced net degradation as well, possibly as a response to a lowering base level downstream. However, degradation appears to have been primarily limited to two locations: a pool was scoured at approximately river station 2+800, and a wedge of sediment roughly one kilometre upstream of the pool was evacuated.

Aggradation of approximately 0.78 m occurred at the boundary between Reaches 7 and 8 and is inferred to be a localized effect of the Bearberry Creek weir.

4.5 Rating Curve Comparison

The rating curves for Bearberry Creek near Sundre are presented in Figure 20. The gauge was established in 1976 and was originally located in Reach 7 at approximately STN 1+000. In late 2004, it was moved to the Cowboy Trail bridge at the boundary between Reaches 9 and 10. Rating curves are available for 1997-2018. The 1997-2005 rating curves must be compared separately to the 2005-2018 curves because of the gauge location change.

The rating curves for 1997-2005 changed little. There was a slight upward shift of the curves between 1997-1999 and 1999-2005 which could represent either channel narrowing or aggradation. Since the thalweg data suggests that the reach is primarily degradational (Section 4.4.2), it is likely that the channel narrowed slightly.

Between 2005 and 2012, the stage lowered relative to discharge. This suggests that either channel degradation or channel widening occurred. The consistent channel lowering identified in the thalweg data suggests that degradation is the likely cause for the rating curve shift.

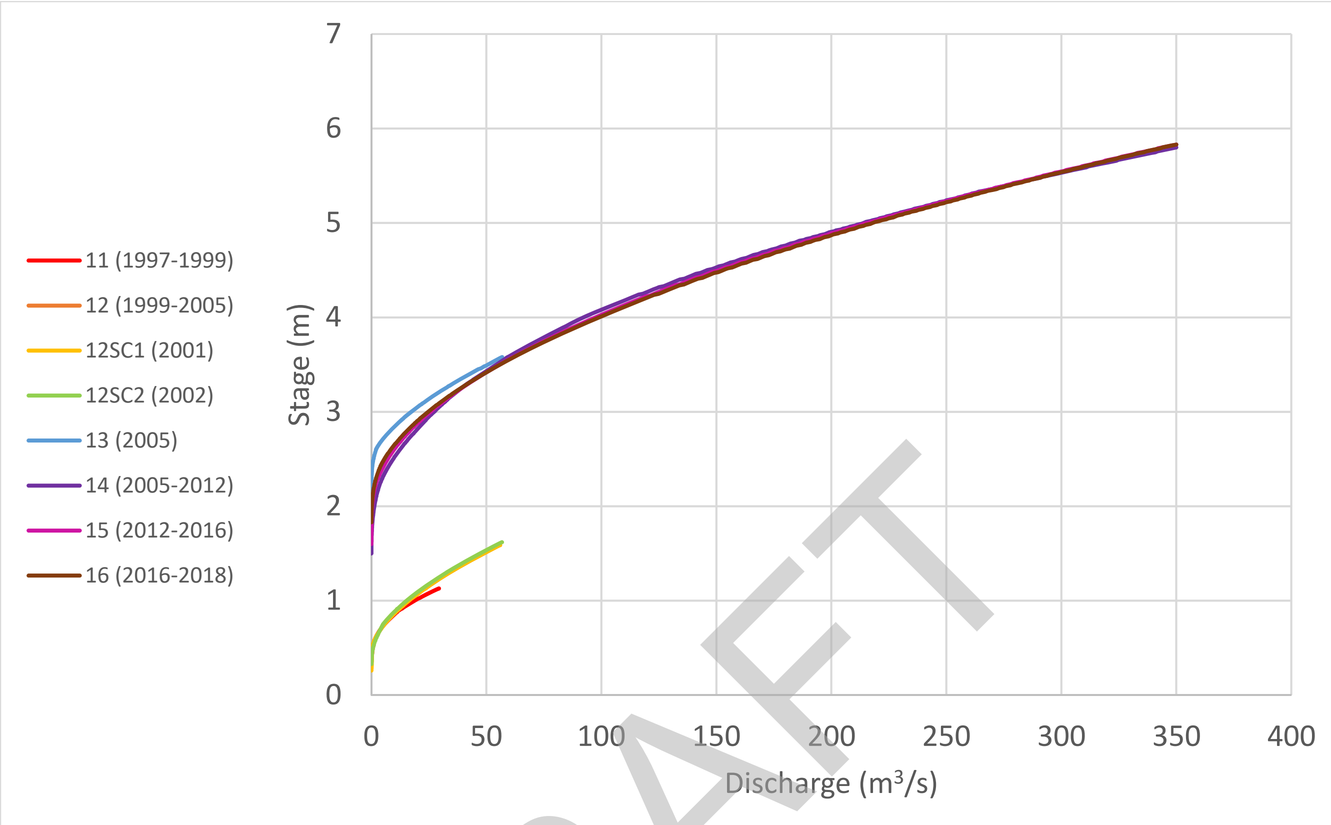

Figure 20: Rating curves for Bearberry Creek near Sundre

5.0 CONCLUSIONS

The results from the channel delineation, cross section, thalweg profile, and rating curve comparisons are summarized and discussed below for each reach. Key characteristics are summarized in Table 8. The channel stability of the reaches is mapped in Figure 14.

5.1.1 Reach 1

Reach 1 of the Red Deer River is comprised of the Gleniffer Reservoir, which has filled most of the valley.

This reach is considered stable due to the presence of the reservoir.

5.1.2 Reach 2

Reach 2 of the Red Deer River is characterized by a broad, wandering channel corridor. The corridor is confined by bluffs in some areas but has migrated in unconfined sub-reaches. A wide active channel corridor consisting of abundant bare sediment surfaces as well as a high percentage of floodplain reactivation (48%) suggest that this reach experiences high sediment transport rates. The active channel typically narrowed over the observed period, which may have decreased the ability of the channel to convey flood flows.

This reach is considered unstable due to the high percentage of floodplain reactivation and possible loss in cross sectional area.

Table 8: Summary of Reach Characteristics

Reach and Description	Floodplain reactivation percentage	Reach Slope (m/m)	Summary of Observations
1—Dickson Dam to STN 13+000	83	0.00041	■ Most of valley submerged under Gleniffer Reservoir
2—STN 13+000 to STN 23+600	48	0.0023	■ Wandering planform ■ Floodplain partly confined by bluffs ■ Abundant vegetated islands ■ Extensive channel corridor movement ■ Narrowing of active channel ■ Localized widening of channel corridor ■ Wide active channel suggests high sediment supply
3—STN 23+600 to James River confluence	52	0.0031	■ Wandering to braided planform ■ Floodplain is primarily unconfined ■ Apparent scour of some vegetated islands ■ Widening of channel corridor in some locations ■ Extensive channel migration within channel corridor ■ Active channel widening and narrowing ■ Channel corridor is confined on left bank by bluffs ■ Wide active channel suggests high sediment supply
4—James River confluence to Bearberry Creek confluence	42	0.0036	■ Braided channel planform ■ Several large islands ■ Local channel constriction near bridge ■ Apparent scour of vegetated islands near bridge ■ Channel corridor migration ■ Active channel widening ■ Aggradation downstream of Bearberry Creek ■ Wide active channel suggests high sediment supply ■ Net bed volume change in measured subreach: 980 m^3/m
5—Bearberry Creek confluence to Bearberry Prairie Natural Area	49	0.0034	■ Wandering to braided channel planform ■ Channel primarily unconfined except near Highway 27 bridge and adjacent to bluffs ■ Channel apparently becomes more braided ■ Channel corridor is split into two forks; most flow was diverted into larger fork ■ Migration of channel corridor ■ Development encroaching onto the floodplain ■ Bank protection present on both sides of channel corridor near bridge ■ Extensive channel migration and avulsion ■ Active channel widening and narrowing ■ Wide active channel suggests high sediment supply ■ Net bed volume change in measured subreach: -2440 m^3/m
6—Bearberry Prairie Natural Area to STN 85+600	45	0.0051	■ Wandering channel planform with localized braiding ■ Some channel confinement adjacent to bluffs ■ Channel has become more single-threaded ■ Active channel primarily widened ■ Abundant migration of the dominant channel and channel corridor ■ Wide active channel suggests high sediment supply

Table 8: Summary of Reach Characteristics

Reach and Description	Floodplain reactivation percentage	Reach Slope (m/m)	Summary of Observations
7—Red Deer River confluence to Bearberry Creek weir	24	0.0057	■ Straight to meandering planform ■ Frequent islands that shifted and vegetated ■ Channel corridor has been straightened ■ Banks are apparently protected with riprap and the alignment is similar in the historic and modern periods ■ Degradation ■ Net bed volume change: -1040 m^3/m
8—Bearberry Creek weir to upstream end of fish passage	75	0.0028	■ Channel corridor was straightened and diverted ■ Fish passage constructed ■ Lack of apparent bars or islands suggest low sediment load ■ Banks are apparently protected with riprap ■ Degradation ■ Net bed volume change: -120 m^3/m
9—Upstream end of fish passage to Cowboy Trail	63	0.0026	■ Single-threaded straight channel corridor ■ Historical channel corridor was highly sinuous ■ No apparent bars or islands present suggesting low sediment supply ■ Degradation ■ Net bed volume change: -210 m^3/m
10—Cowboy Trail to STN 13+300	63	0.0023	■ Typically single-threaded, torturous meandering channel ■ Occasional islands and side bars point to low-moderate sediment supply ■ Extensive channel corridor migration at outer bends and meander cut-offs ■ Localized degradation due to pool development and evacuation of a sediment wedge ■ Net bed volume change in measured subreach: -920 m^3/m
11—STN 13+300 to STN 14+200	23	0.00011	■ Meandering channel corridor with low sinuosity ■ No apparent bars or islands present suggesting low sediment supply ■ Limited observed migration of the channel
12—STN 14+200 to STN 17+100	44	0.0020	■ Single-threaded, torturous meandering channel ■ Rare small islands and side bars present suggesting limited sediment supply ■ Extensive channel corridor migration at outer bends and meander cut-offs

5.1.3 Reach 3

Reach 3 of the Red Deer River is typically braided with a wide channel corridor. The channel corridor margins have migrated on the outside of some bends over time, although the bank alignment appears to be more stable over time at locations where the channel is confined by bluffs. The active channel has primarily narrowed, and migration and avulsion of dominant and sub-dominant channels is common. Approximately 52% of the modern active channel was floodplain/forested island in the 1960s. An abundance of bare sediment surfaces as well as the high percentage of floodplain reactivation suggest that this reach experiences high sediment transport rates. Over the observed period, the active channel width has increased in some locations and decreased in others.

Widening may indicate an increased ability of the channel to convey flood flows in those areas, while narrowing may have locally decreased the ability of the channel to convey flood flows.

This reach is considered unstable due to the high percentage of floodplain reactivation.

5.1.4 Reach 4

Reach 4 of the Red Deer River is typically braided with a wide channel corridor and several large vegetated islands. The channel corridor is confined in the vicinity of Sundre at the upstream end of the reach but widens downstream over a distance of a few kilometres. The channel corridor has typically narrowed over the observed period due to the abandonment of sub-dominant channels, but the active channel has widened by up to approximately 50%. Dominant and sub-dominant channel migration, island scour, and avulsion are common on this reach, which has had a floodplain reactivation of 42% since the 1960s. An abundance of bare sediment surfaces as well as the high floodplain reactivation percentage suggest that this reach experiences high sediment transport rates.

Reach 4 appears to receive abundant sediment supply from upstream on the Red Deer River and from Bearberry Creek. The thalweg and cross section analyses show that the dominant channel has been locally aggrading, and it has moved to a new location and adopted a wider, more rectangular geometry. Channel widening has increased the cross sectional area of the channel, which has likely increased its ability to convey flood flows. However, local aggradation may increase the susceptibility of the channel to avulsion.

This reach is considered unstable due to the high percentage of floodplain reactivation.

5.1.5 Reach 5

Reach 5 of the Red Deer River is characterized by a broad, wandering channel corridor with localized braiding. Historically, the channel was divided into two forks, but most flow has been diverted to the southernmost fork. This may have contributed to degradation in the reach, which was observed in the thalweg data.

Channel migration and avulsion are common in this reach; 49% of the active channel area was created after the 1960s. An abundance of bare sediment surfaces as well as the high floodplain reactivation percentage suggest that this reach experiences high sediment transport rates. Over the observed period, the active channel belt has widened in some locations and narrowed in others. Channel widening may indicate an increased ability of the channel to convey flood flows in those areas, while channel narrowing may have locally decreased the ability of the channel to convey flood flows. Flooding was observed on Reach 5 during the 2013 high flow event (Golder, 2014).

This reach is considered unstable due to the high percentage of floodplain reactivation.

5.1.6 Reach 6

Reach 6 of the Red Deer River is characterized by a broad, wandering channel corridor with localized braiding. The channel corridor margins have migrated in some locations but have remained stable where they run adjacent to bluffs on the downstream portion of the right bank. Approximately 45% of the modern active channel was floodplain/forested island in the 1960s. An abundance of bare sediment surfaces as well as the high floodplain reactivation percentage suggest that this reach experiences high sediment transport rates. The active channel width typically increased over the observed period, which may have increased the ability of the channel to convey flood flows. Flooding was observed on Reach 6 during the 2013 high flow event (Golder, 2014).

This reach is considered unstable due to the high percentage of floodplain reactivation.

5.1.7 Reach 7

Reach 7 of Bearberry Creek is characterized by straight, engineered banks that confine a meandering channel with frequent islands. The banks are protected by riprap and bank alignment is similar in the 1960s and in 2017. Mid-channel bars have typically shifted upstream and become stabilized with vegetation. Approximately 24% of the modern active channel was floodplain/forested island in the 1960s. The presence of bars suggest that the channel has moderate sediment supply.

The channel has developed a more skewed geometry and has degraded over the observed period; however, the cross sectional area has not changed substantially, suggesting that the ability of the channel to convey flood flow has changed little. Flooding was observed on Reach 7 during a high flow event in 2005.

This reach is considered stable due to the low percentage of floodplain reactivation and lack of substantial change in the cross sectional area. However, stability is dependent on whether the riprap is adequate and maintained in good condition. Significant bank erosion did occur in the reach during the 2005 event (Golder, 2018b). The stream could be expected to experience more meander migration if it was less constrained by existing bank erosion protection.

5.1.8 Reach 8

Reach 8 of Bearberry Creek is straight with engineered banks. Historically, the channel corridor was sinuous, and a fish passage has been constructed in the vicinity of the historical channel. Approximately 75% of the modern active channel was floodplain/forested island in the 1960s, but the high level of floodplain reactivation is attributed to channel straightening. No apparent side, point, or mid-channel bars are present, suggesting that the reach has a low sediment supply.

The channel has cut into its bed and its geometry has evolved from an approximately trapezoidal shape to a more skewed one. The cross sectional area has not changed substantially, suggesting that the ability of the channel to convey flood flow has changed little. Flooding was observed on Reach 8 during a high flow event in 2005.

This reach is considered stable due to the lack of substantial change in the cross sectional area, provided the riprap is adequate and maintained in good condition. However, stability is dependent on whether the riprap is adequate and maintained in good condition. The channel bed has been evolving into a geometry associated with a meandering planform. The stream could be expected to experience more meander migration if it was less constrained by existing bank erosion protection.

5.1.9 Reach 9

Reach 9 of Bearberry Creek is single-threaded with no visible bars or islands. The channel was historically meandering but was straightened prior to 1992. The natural channel alignment for this reach is meandering, and no bank protection is apparent from the air photos. Approximately 63% of the modern active channel was floodplain/forested island in the 1960s, but some floodplain reactivation can be attributed to channel straightening. The absence of visible bare sediment suggests that sediment supply to the reach is low.

The reach appears to have degraded. It also experienced a minor loss to cross sectional area over the observed period, which may indicate a slight reduction of the ability of the channel to convey flood flow.

This reach is considered unstable due to the expectation of a high level of floodplain reactivation and the loss of cross sectional area. Since there does not appear to be bank protection present, the channel can be expected to develop a more meandering planform in the future.

5.1.10 Reach 10

Reach 10 of Bearberry Creek is single-threaded with a torturous meandering planform. Extensive channel corridor migration at meander bends as well as avulsion due to meander bend cut-offs were frequently observed. Approximately 63% of the modern active channel was floodplain/forested island in the 1960s. The presence of occasional islands and side bars suggest that the reach receives a low to moderate amount of sediment supply.

The observed cross sections show little change in cross sectional area or geometry, suggesting that the ability of the channel to convey flood flow has not changed substantially. However, the thalweg data show that the reach has experienced local degradation due to the formation of a new pool and the evacuation of a sediment wedge. The reach may be responding to a change in base level downstream.

This reach is considered unstable due to the high percentage of floodplain reactivation.

5.1.11 Reach 11

Reach 11 of Bearberry Creek is characterized by a single-threaded, meandering channel corridor with a low sinuosity. The channel alignment has remained approximately stable over the observed period. Approximately 23% of the modern active channel was floodplain/forested island in the 1960s. No apparent bars or islands are present, suggesting that sediment supply to the reach is low. Channel slope in this reach is gentler than both upstream and downstream. It is possible that the channel is constrained by a geologic control.

It is unknown whether the ability of the channel to convey flood flows has changed over time, but minimal visible change in width suggests that the channel area may have remained stable.

This reach is considered stable due to the low percentage of floodplain reactivation and lack of evidence for change in the cross sectional area.

5.1.12 Reach 12

Reach 12 of Bearberry Creek is single-threaded with a torturous meandering planform. Extensive channel corridor migration at meander bends as well as avulsion due to meander bend cut-offs were frequently observed. Approximately 44% of the modern active channel was floodplain/forested island in the 1960s. Islands and side bars are rare, suggesting that sediment supply is low. Over the observed period, the active channel belt has slightly widened in some locations and narrowed slightly in others. Channel widening may indicate an increased ability of the channel to convey flood flows in those areas, while channel narrowing may have locally decreased the ability of the channel to convey flood flows.

This reach is considered unstable due to the high percentage of floodplain reactivation.

Signature Page

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https://golderassociates.sharepoint.com/sites/16980g/technical work/08_channel stability investigation/03_reporting/report/rev0/1783057-055-r-rev0_channel_stability_20190723.docx

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APPENDIX A

Cross Section Comparison

Table 1: Cross Section Geometry for 1992 and 2017

Reach	Cross Section ID	Km	Cross sectional Area (m^2)		Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2017	1992	2017	1992	2017	1992	2017	
Reach 4 (Red Deer River)—James River confluence to Bearberry Creek confluence	4	55036	200	180	380	330	1.9	1.5	0.54	0.53	▪ Braided channel ▪ Dominant and sub-dominant channels have relatively low width to depth ratios ▪ Side channels widen approximately 20-30 m ▪ Possible aggradation of ~1 m near right bank ▪ Reduction in channel area ▪ Neither left- nor right-handed and no skew ▪ Straight channel corridor ▪ Indistinct thalweg ▪ Approximately 5 channels present in 1992 and 4 present in 2017 ▪ Thalweg elevation increased by approximately 0.4 metres, but dominant channel elevation remains approximately the same ▪ Mid-channel island toward left bank of channel corridor grew approximately 150 m in width ▪ New mid-channel island near centre of channel ▪ Location of dominant channel remains approximately the same. Second-largest channel shifts approximately 160 metres to right
	8	56477	160	150	250	220	1.7	2.0	0.63	0.70	▪ Braided channel ▪ Dominant and sub-dominant channels have low width to depth ratios in 1992, but they increase by 2017 ▪ Minimal change to cross-sectional area ▪ Neither left- nor right-handed and no skew ▪ Straight channel corridor ▪ Indistinct thalweg ▪ In 1992, flow is approximately equally distributed within 4 channels. By 2017, most flow is centered on 1-2 new channels ▪ Channel has degraded approximately 0.4 m. ▪ Dominant channel develops in left-center portion of channel corridor ▪ Near the right side of the flow corridor, ~40 cm of aggradation has occurred. ▪ Island on left-center side of channel corridor has been eroded

Table 1: Cross Section Geometry for 1992 and 2017

Reach	Cross Section ID	Km	Cross sectional Area (m^2)		Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2017	1992	2017	1992	2017	1992	2017	
Reach 4 (Red Deer River)—James River confluence to Bearberry Creek confluence	13	58708	120	170	270	210	3.2	1.6	0.46	0.80	■ Wandering to braided channel ■ High width to depth ratio ■ Narrowing of active channel width ■ Channel area increases ■ Dominant channel changes from right-handed and skewed to right to having neither left- nor right-handedness and no skew ■ Cross-section is situated on slight bend of channel corridor. Outer bank of bend is on right side of channel corridor ■ Thalweg changes from distinct to indistinct ■ Dominant channel carries the majority of flow with approximately 1-2 sub-dominant channels sharing a small fraction of flow ■ No apparent channel-wide aggradation or degradation ■ No apparent formation/loss of islands ■ Sediment accumulation of ~4 m in the location of the 1992 dominant channel ■ Dominant channel widens and shifts to right approximately 360 m
Reach 5 (Red Deer River)—Bearberry Creek confluence to Bearberry Prairie Natural Area	18	59854	230	170	300	220	2.3	2.0	0.77	0.75	■ Wandering to braided channel ■ Width to depth ratio increases from moderate to high ■ Channel area appears to have decreased since 1992 due primarily to a reduction in active channel width, but large there is large uncertainty in the 1992 active channel width ■ Dominant channel changes from slightly lefthanded with no skew to right-handed with a slight right skew ■ Straight channel corridor ■ Thalweg changes from distinct to moderately distinct ■ Dominant channel carries the majority of flow with a few sub-dominant channels sharing a small fraction of flow ■ Approximately 2 new sub-dominant channels formed ■ No apparent channel-wide aggradation or degradation ■ A mid-channel bar develops in the location of the former thalweg ■ Bar growth of approximately 40 cm apparent on right side of channel belt ■ Dominant channel widens to the left approximately 75 m

Table 1: Cross Section Geometry for 1992 and 2017

Reach	Cross Section ID	Km	Cross sectional Area (m^2)		Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2017	1992	2017	1992	2017	1992	2017	
Reach 5 (Red Deer River)—Bearberry Creek confluence to Bearberry Prairie Natural Area	22	61408	250	93	190	64	2.1	2.6	1.3	1.5	■ Single-threaded channel ■ Decrease in width to depth ratio from high to low ■ Decrease in channel width of over 100 m ■ Channel area appears to have decreased since 1992 due primarily to a reduction in active channel width, but large there is large uncertainty in the 1992 active channel width ■ Left-handedness and left skew develop ■ Channel corridor is confined at cross-section ■ Channel shape changes from broad and narrow with no distinct thalweg to a more incised, narrower, U-shaped channel with a bar on the right bank and a distinct thalweg ■ Qualitatively appears to be little net change in average bed elevation ■ No apparent islands
Reach 7 (Bearberry Creek)—Red Deer River confluence to Bearberry Creek weir	2	281	63	66	45	51	2.1	2.6	1.4	1.3	■ Single-threaded channel ■ High width to depth ratio ■ Channel width remains approximately the same ■ Channel appears to have migrated approximately 5 m to the right ■ Cross-sectional area remains similar ■ Shifts from righthandedness with a slight right skew to left-handedness with no skew ■ Straight channel corridor ■ Channel has degraded approximately 0.8 m over an ~11 m wide portion of the bed, forming a rectangular-shaped incised channel with the thalweg near its right bank ■ No apparent islands

Table 1: Cross Section Geometry for 1992 and 2017

Reach	Cross Section ID	Km	Cross sectional Area (m^2)		Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2017	1992	2017	1992	2017	1992	2017	
Reach 7 (Bearberry Creek)—Red Deer River confluence to Bearberry Creek weir	10	1038	190	190	55	56	5.5	5.6	3.5	3.4	■ Single-threaded channel ■ Medium width to depth ratio ■ Slight channel widening and reduction in depth ■ Channel area appears to have remained the same ■ Left bank lowers approximately 1 m—no apparent mechanism. Bank of 1992 cross-section may have been raised for modeling purposes ■ Slight righthandedness shifts to slight left-handedness ■ No skew ■ Straight channel corridor ■ Indistinct thalweg—channel is approximately trapezoidal ■ Channel degrades approximately 0.5 m ■ No apparent islands
Reach 8 (Bearberr Creek)—Bearberry Creek weir to upstream end of fish passage	16	~1550 (station 256)	70	77	35	40	2.8	4.2	2.0	1.9	■ Single-threaded channel ■ Channel widens ■ Average depth remains similar, but max depth increases ■ Channel shifts from a trapezoidal shape with no skew to a right-handed, right-skewed shape with an incised area near the right bank and a bar on the left bank ■ Straight channel corridor, though bend appears to be developing ■ Indistinct thalweg in 1992; thalweg is more distinct in 2017 ■ Degradation of approximately 1 m on the right side of the channel and aggradation of approximately 0.9 meters on the left side. ■ No apparent islands

Table 1: Cross Section Geometry for 1992 and 2017

Reach	Cross Section ID	Km	Cross sectional Area (m^2)		Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2017	1992	2017	1992	2017	1992	2017	
Reach 9 (Bearberry Creek)—Upstream end of fish passage to Cowboy Trail	20	1936	86	78	38	39	3.6	3.4	2.3	2.0	▪ Single-threaded channel ▪ Medium width to depth ratio ▪ Slight channel narrowing ▪ Right bank has migrated to the left approximately 1-3 m ▪ Slight decrease to channel area ▪ Trapezoidal-shaped channel with no skew ▪ Straight channel corridor ▪ Indistinct thalweg ▪ Channel bank tops have aggraded approximately 0.2 m (possibly from overbank sedimentation) ▪ Channel has degraded approximately 0.5 m. ▪ No apparent islands
Reach 10 (Bearberry Creek)—Cowboy Trail to STN 13+300	29	3118	14	16	19	24	1.1	1.2	0.73	0.66	▪ Single-threaded channel ▪ Channel has widened approximately 1 m on each side ▪ Channel area has remained approximately similar ▪ Righthandedness with a right skew ▪ Cross-section is located near the apex of a meander in the channel corridor ▪ Thalweg becomes more distinct ▪ Left side of channel has aggraded approximately 0.1-0.4 m ▪ The center of the channel has aggraded up to approximately 0.5 m ▪ No apparent islands

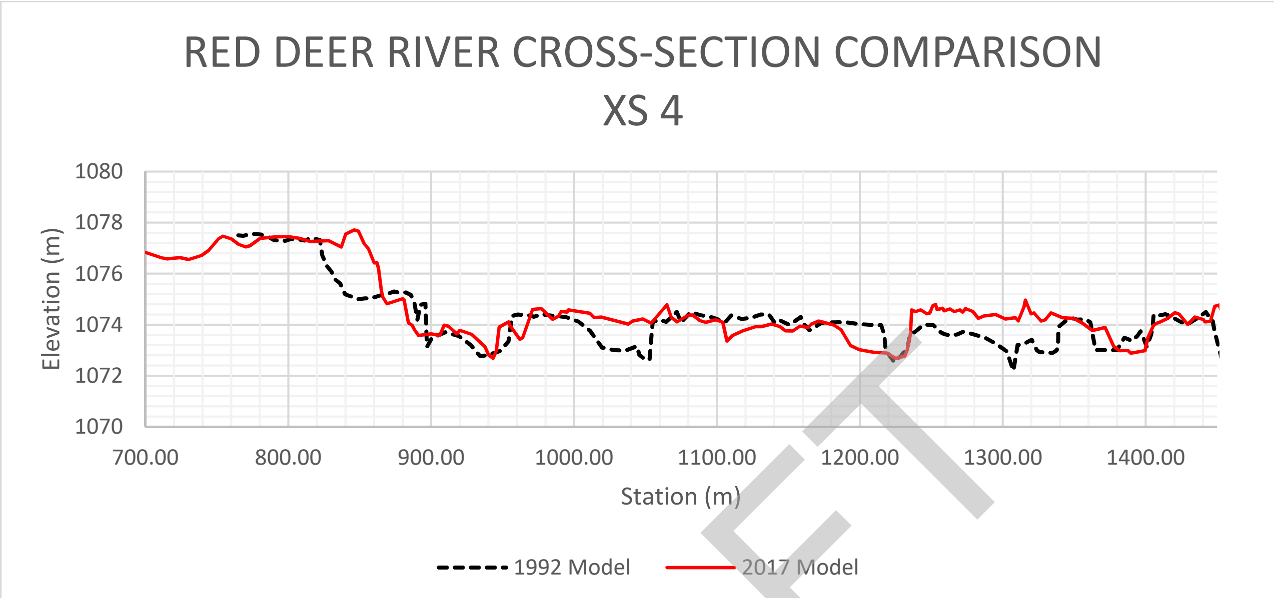
Table 1: Cross Section Geometry for 1992 and 2017

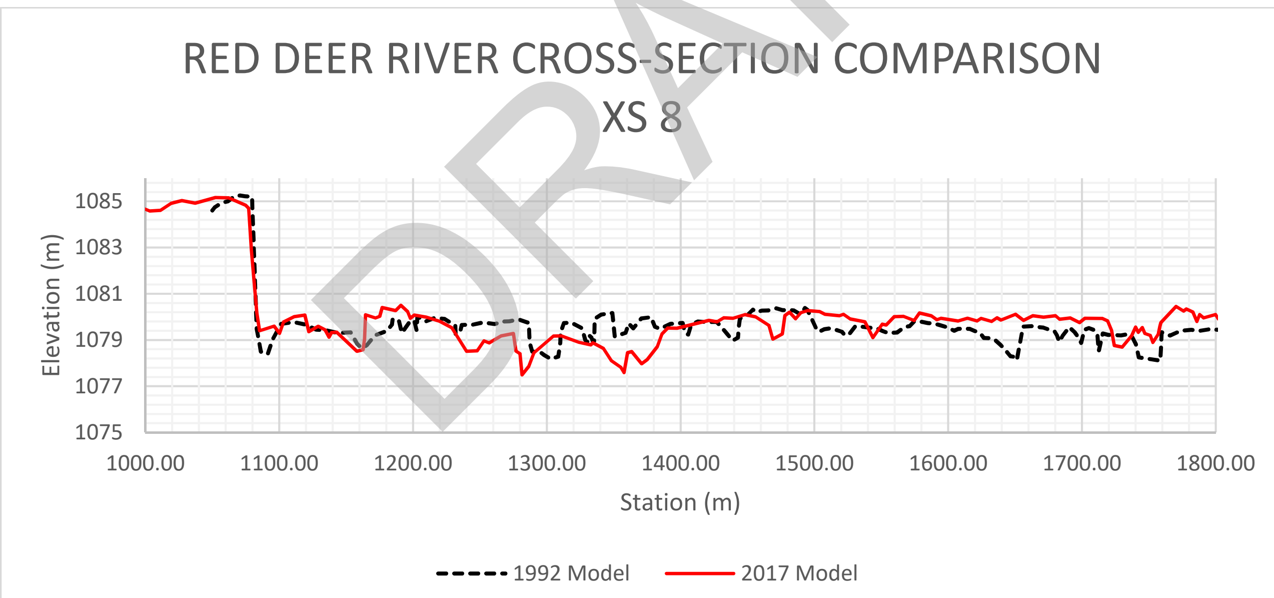
Reach	Cross Section ID	Km	Cross sectional Area (m^2)		Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2017	1992	2017	1992	2017	1992	2017	
Reach 10 (Bearberry Creek)—Cowboy Trail to STN 13+300	37	4413	11	16	11	16	1.3	1.7	1.0	1.1	■ Single-threaded channel ■ Low width to depth ratio ■ Channel has widened approximately 5 m, primarily due to leftward migration of the left bank ■ Increase to cross-sectional area ■ Very slight left-handedness shifts to very slight righthandedness with a slight right skew ■ Cross-section is located near the apex of a meander in the channel corridor ■ Indistinct thalweg ■ Little change in bed elevation ■ No apparent islands
	41	5354	12	16	9.1	13	1.5	1.9	1.3	1.2	■ Single-threaded channel ■ Channel has widened ■ Cross-sectional area has increased ■ Channel shifts from very slightly right-handed to very slightly left-handed ■ No skew ■ Cross-section is located near the centre of a small meander bend ■ Indistinct thalweg ■ Channel bed has degraded by approximately 0.2 m ■ The bank tops have aggraded by approximately 0.2 m (possibly from overbank sedimentation) ■ No apparent islands

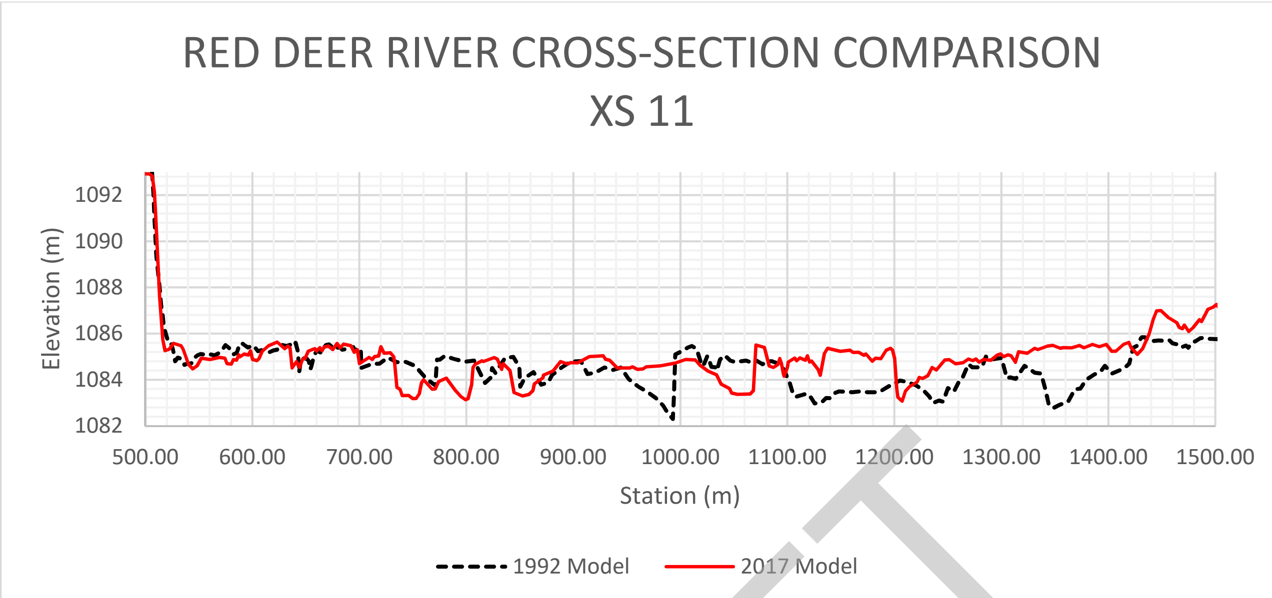
Table 1: Cross Section Geometry for 1992 and 2017

Reach	Cross Section ID	Km	Cross sectional Area (m^2)		Bankfull Width		Maximum Bankfull Depth		Average Bankfull Depth		Description
			1992	2017	1992	2017	1992	2017	1992	2017	
Reach 10 (Bearberry Creek)—Cowboy Trail to STN 13+300	46	6297	41	27	17	18	3.0	2.2	2.5	1.5	■ Single-threaded channel ■ Right bank migrated to right approximately 4 meters ■ Channel depth apparently decreases ■ Cross-sectional area apparently decreased ■ Floodplain appears to have lowered by a meter—no apparent mechanism. Bank of 1992 cross-section may have been raised for modeling purposes ■ Slight right skew develops ■ Cross-section is located just downstream of sharp (~90°) bend in channel corridor ■ Indistinct thalweg ■ Right bank toe aggraded approximately 0.5 m (possible bank slump) ■ No apparent islands

1.0 REACH 4: JAMES RIVER CONFLUENCE TO BEARBERRY CREEK CONFLUENCE



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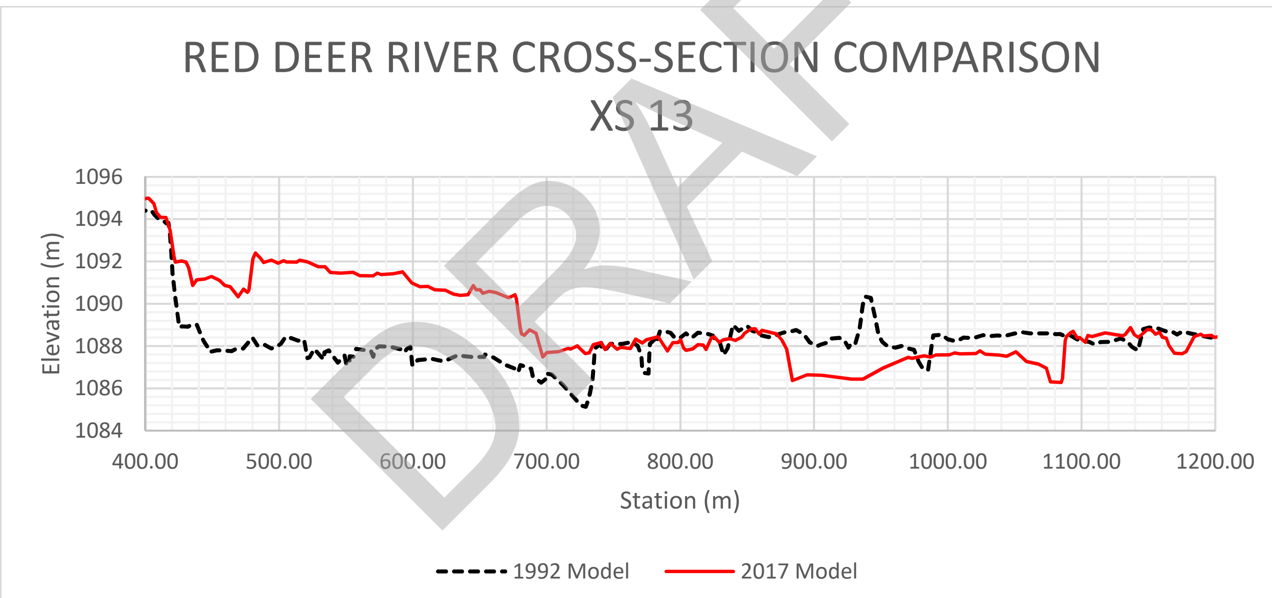
Station (m)
1992 Model
2017 Model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700.00
800.00
900.00
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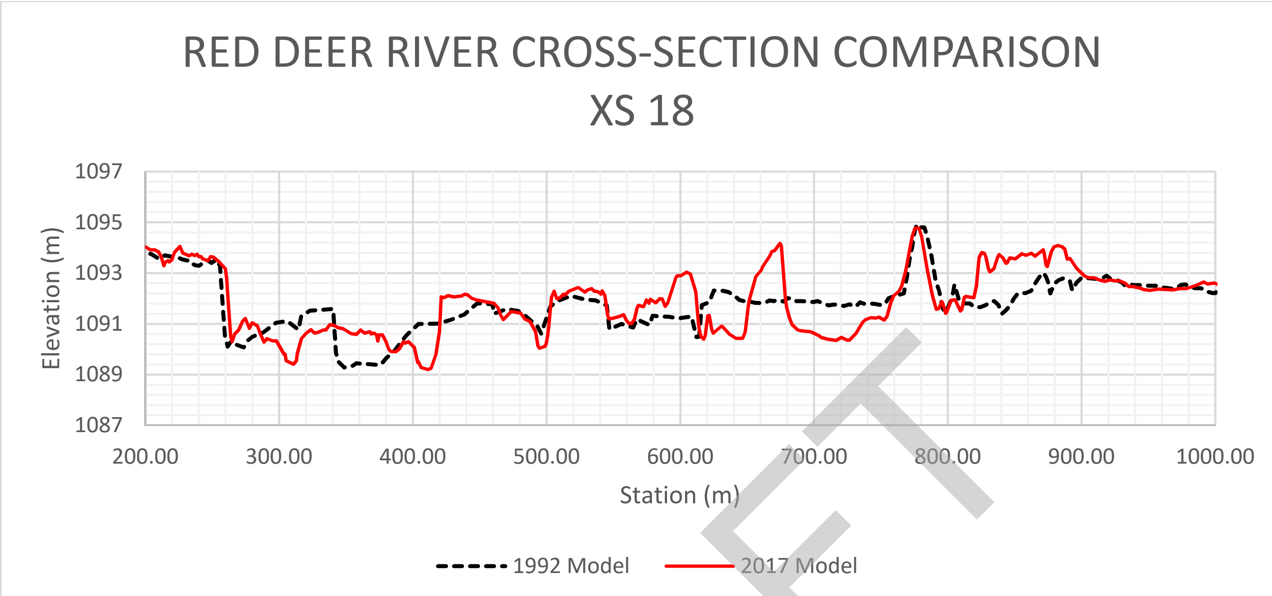
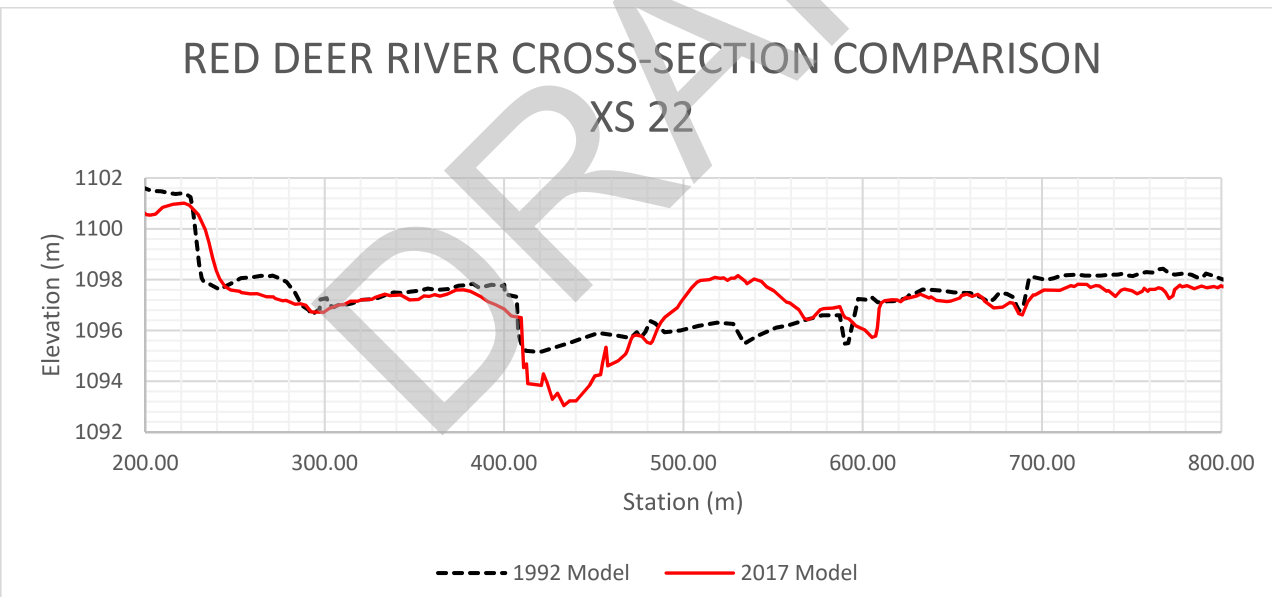
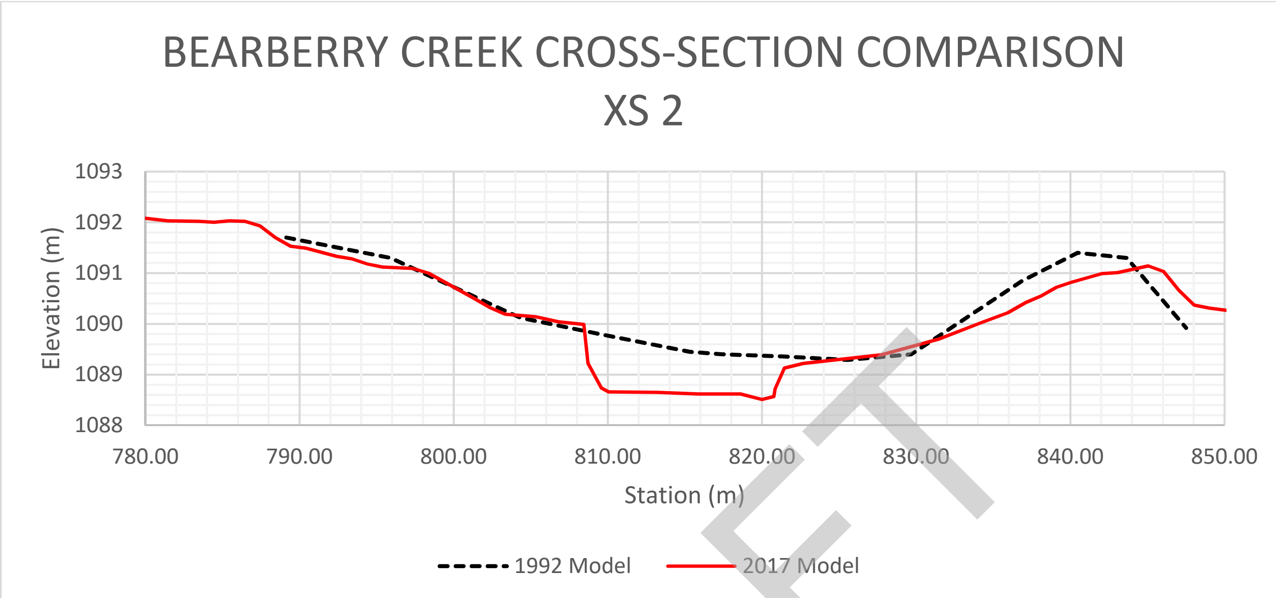
Station (m)
1992 Model
2017 Model

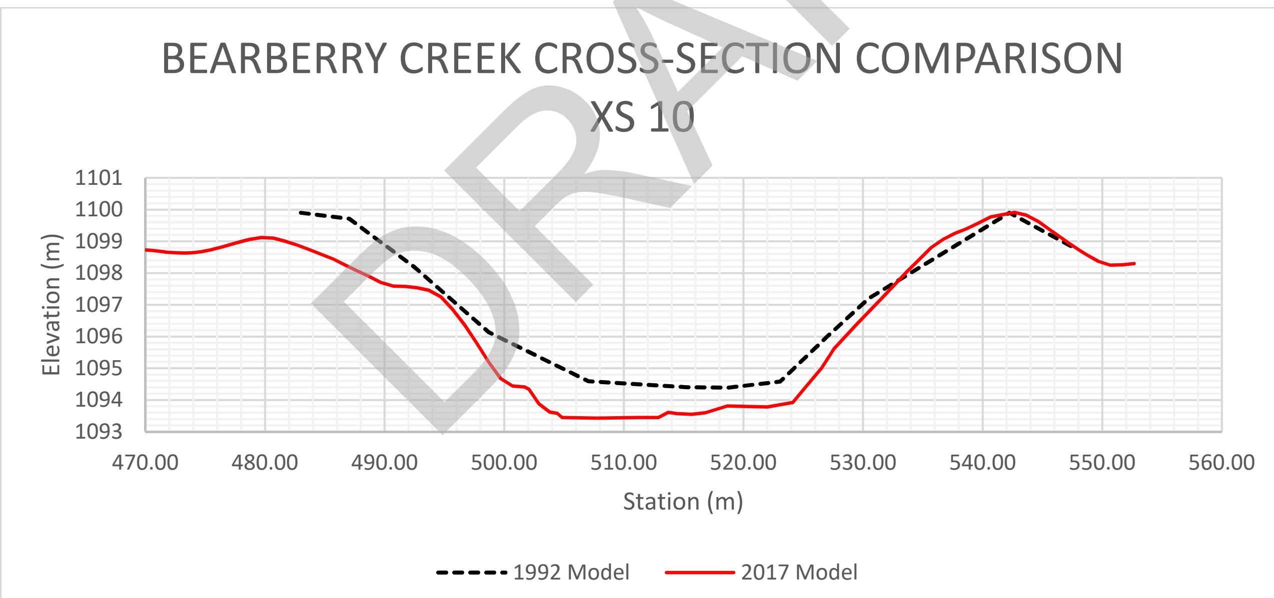
2.0 REACH 5: BEARBERRY CREEK CONFLUENCE TO BEARBERRY PRAIRIE NATURAL AREA



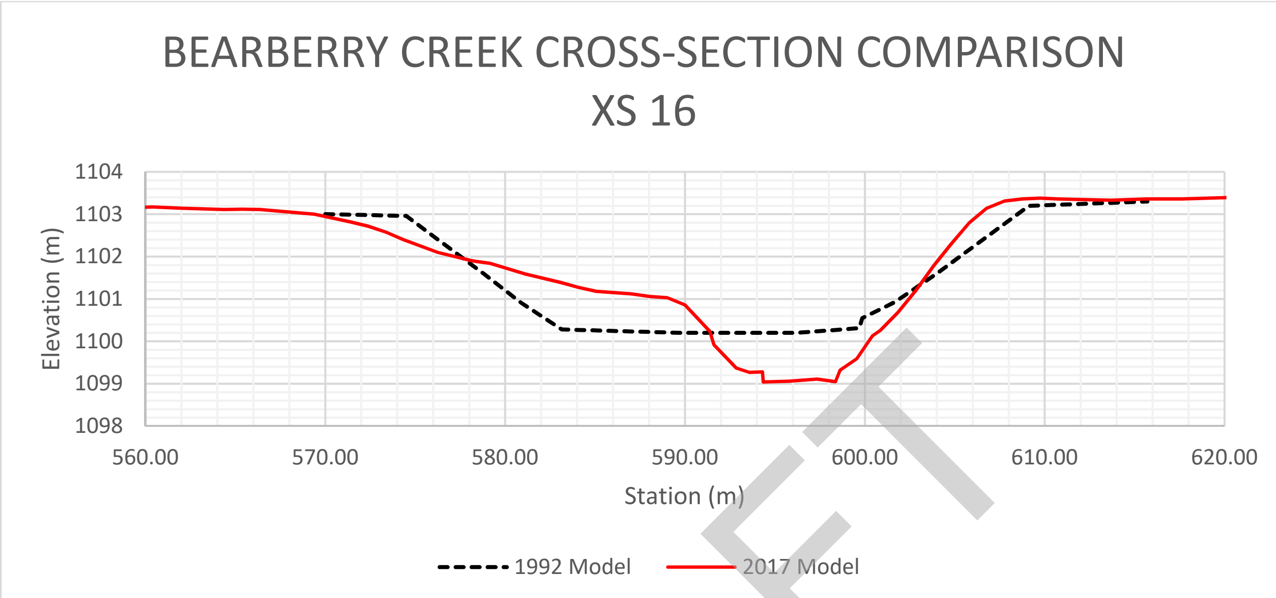


3.0 REACH 7: RED DEER RIVER CONFLUENCE TO BEARBERRY CREEK WEIR

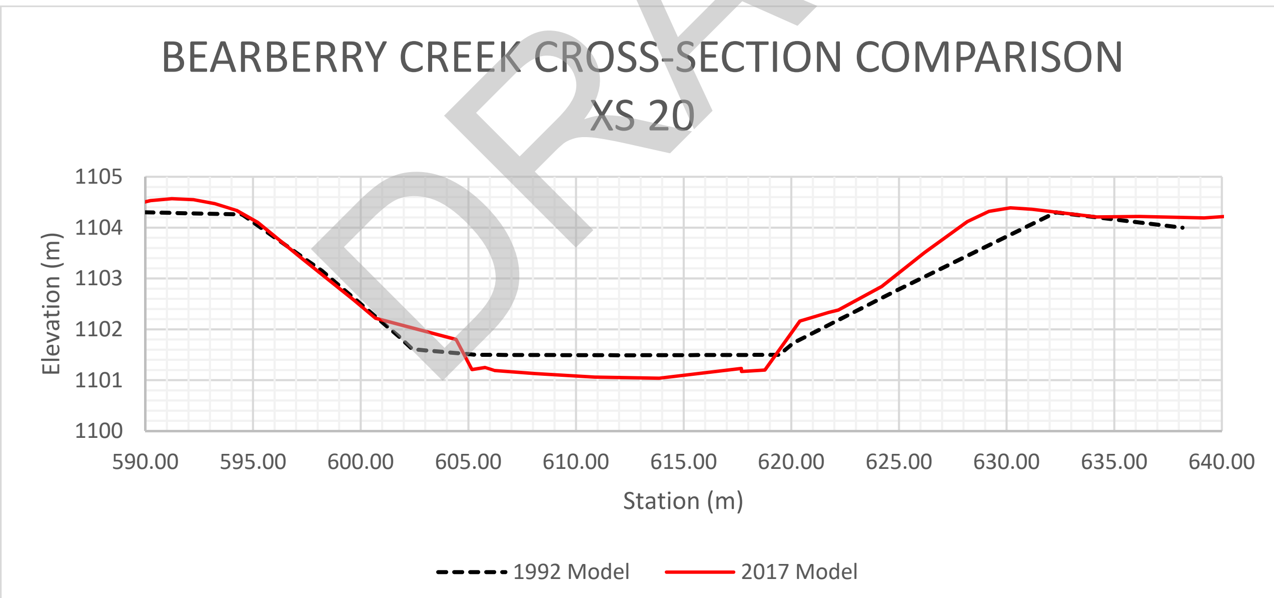




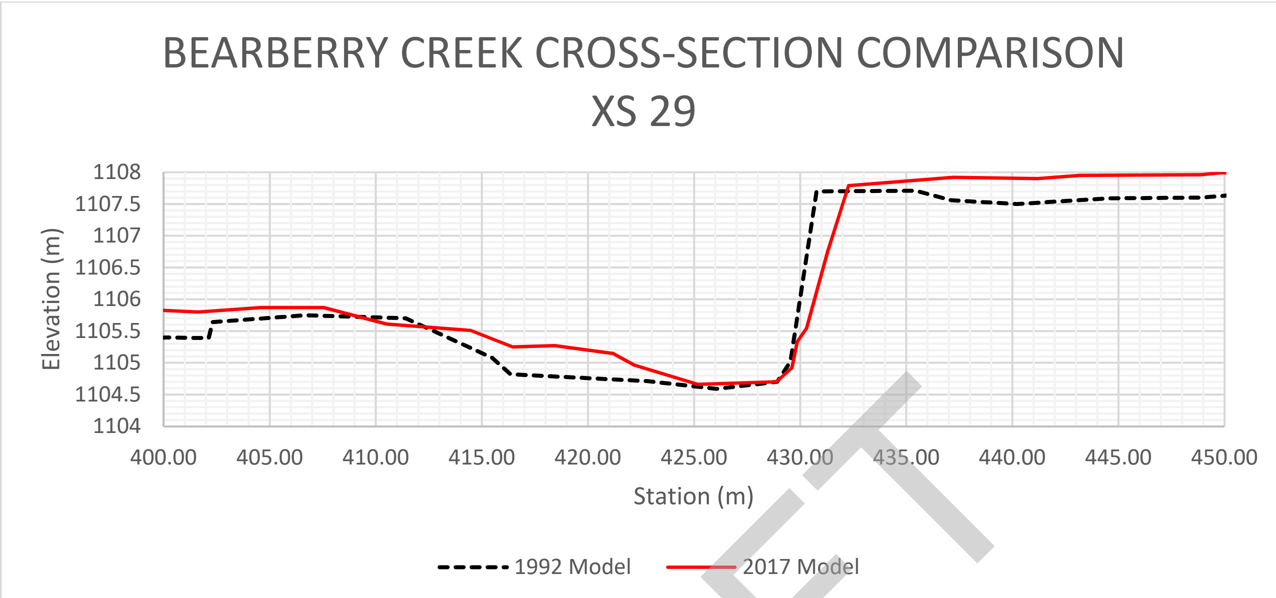
4.0 REACH 8: BEARBERRY CREEK WEIR TO UPSTREAM END OF FISH PASSAGE

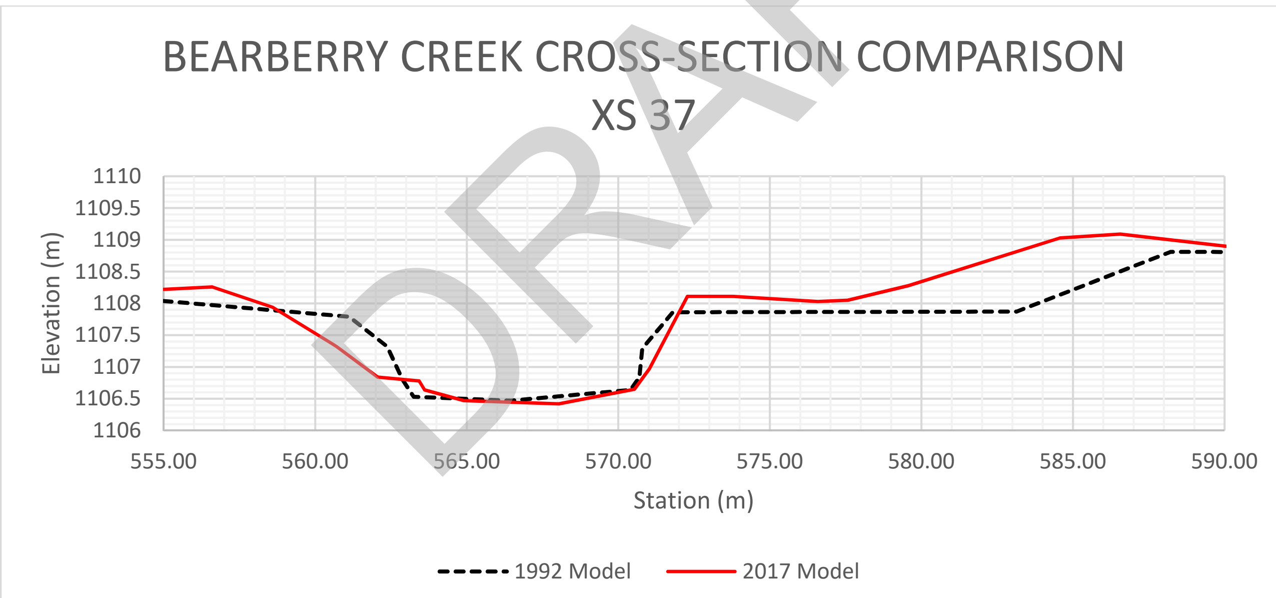


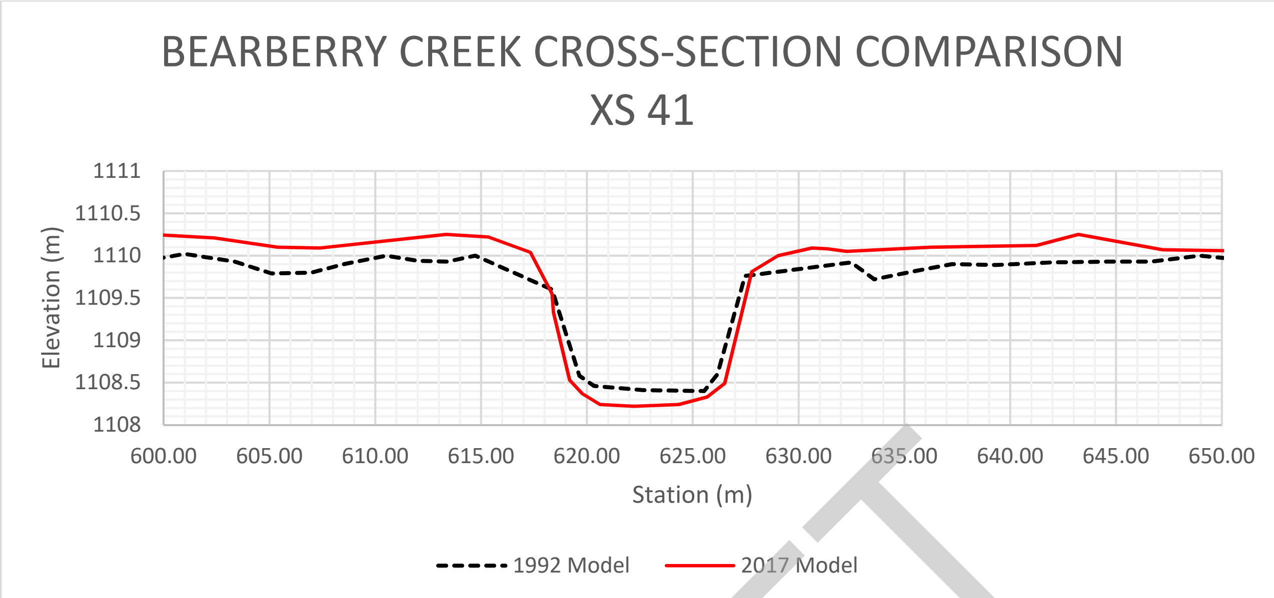
5.0 REACH 9: UPSTREAM END OF FISH PASSAGE TO COWBOY TRAIL

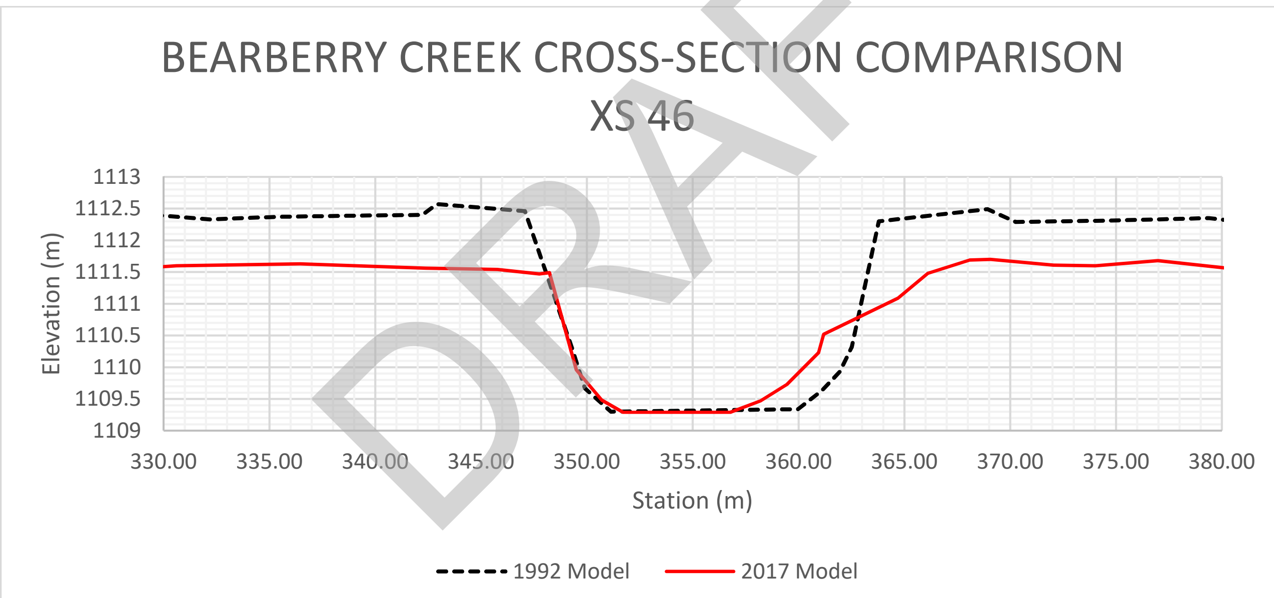


6.0 REACH 10: COWBOY TRAIL TO STN 13+300






BEARBERRY CREEK CROSS-SECTION COMPARISON
XS 41
1111
1110.5
1110
1109.5
1109
1108.5
1108
Elevation (m)
600.00
605.00
610.00
615.00
620.00
625.00
630.00
635.00
640.00
645.00
650.00
Station (m)
1992 Model
2017 Model


BEARBERRY CREEK CROSS-SECTION COMPARISON
XS 46
1113
1112.5
1112
1111.5
1111
1110.5
1110
1109.5
1109
Elevation (m)
330.00
335.00
340.00
345.00
350.00
355.00
360.00
365.00
370.00
375.00
380.00
Station (m)
1992 Model
2017 Model

APPENDIX B

Historical Aerial Imagery Processing Memorandum

TECHNICAL MEMORANDUM

DATE July 22, 2019 **Project No.** 1783057-51-TM-Rev0

TO Jane Eaket
Alberta Environment and Parks

CC Rowland Atkins, Wolf Ploeger, and Dejiang Long

FROM Peter Thiede
Golder Associates **EMAIL Peter_Thiede@Golder.com**

HISTORICAL AERIAL IMAGERY PROCESSING UPPER RED DEER RIVER HAZARD STUDY

1.0 INTRODUCTION

The Channel Stability Component of the Upper Red Deer River Hazard Study required the use of historical aerial photography to support technical analysis and mapping activities. Golder Associates Ltd. (Golder) took a lead role in obtaining and processing the historical aerial imagery with the aerial triangulation, stereo-model and orthorectification tasks outsourced to Tarin Resource Services Ltd. (Tarin). This memorandum provides an overview of the processing methodology, the results of quality assurance checks, and a description of the historical aerial imagery deliverables.

2.0 METHODOLOGY

The historical aerial images selected for the Upper Red Deer River Hazard Study were obtained in a scanned.TIF format from Alberta Environment and Parks (AEP) in April 2018. The images were processed according to the specifications as stated in AEP's Terms of Reference (TOR) and the guidelines published in '*General Specifications for Acquiring Aerial Photography*' (2014). Photographs from 1962 and 1963 were chosen to cover the Red Deer River and Bearberry Creek in the study area. Table 1 provides an overview of the photography used, image scale, and acquisition dates.

Camera calibration reports (for 1962 and 1963) and calibrated focal lengths were also provided by AEP and were used in the image processing.

The raw greyscale images were reviewed for quality assurance and spatial coverage of the project area. The quality and consistency of all images was found to be good. No significant physically damage of the negatives (e.g., scratches), or missing fiducial markings were identified.

On some images, it was found that the high resolution photogrammetric scanner had skipped one or more rows during the scanning process and the skipped gap was filled in with the same values as the last scanned row. This type of error has a negative effect on the accuracy (horizontal and vertical) of the aerial triangulation and will create an artificial vertical step when models are observed in 3D software. The specific distribution of the scanning errors (i.e., near the edge of the frame), allowed for the mitigation of the errors by manual selection of tie points during the aerial triangulation process. However, these scanning errors were not removed, and are still present in the scanned digital frames, therefore vertical steps and horizontal shifts will be observed in a 3D stereoscopy environment.

Overall, the image quality was considered sufficient to proceed with aerial triangulation, stereo model creation and orthorectification.

Table 1: Historical Imagery Processed for the Upper Red Deer River Hazard Study

Extent	Photo Year	Photo Scale	Film Roll No.	Frames used in orthomosaic	Frames processed for AT	Acquisition date(s)
Red Deer River north of Highway 587	1962	1: 31,680	AS0827	5,6,7,8,9, 97,98,99,100,101, 102,103,206,207, 208	5,6,7,8,9,97,98,99, 100,101,102,103,206, 207,208	07/18/1962
Bearberry Creek and Red Deer River south of Highway 587	1963	1: 31,680	AS0870	11,12,13,14,15,84, 85,86,87,88,89	11,12,13,14,15,84,85, 86,87,88,89	05/14/1963 and 06/13/1963
			AS0871	5,6,7,8,9,10,88,89, 90,91,92,93,94,174, 175,176,177,178	5,6,7,8,9,10,88,89,90, 91,92,93,94,174,175, 176,177,178	05/14/1963 and 07/14/1963
			AS0872	-	-	05/14/1963

The images were orthorectified using OrthoMaster software by Trimble Inpho and the AltaLIS 1:20,000 scale digital elevation model (DEM). Image fiducials were identified on each image, however this could only be done accurately on the images with clear fiducials; all others were approximate. Prior to orthorectifying images, OrthoEngine was configured to run at least 30 iterations for the bundle adjustment with an earth curvature value of 6,378,110.

During the orthorectification process, a total of thirty-eight (38) features suitable as ground control points (GCP) were selected. GCPs were typically anthropogenic features such as roads, trails and buildings, positively identifiable on a LiDAR hillshade image, a supplied current orthophoto and on the historical images. The distribution of Ground Control Points (GCPs) followed the recommendation of '*General Specifications for Acquiring Aerial Photography*'. Most images contained at least one GCP. The root mean squared error (RMSE) of the GCP data was within 1.47 (X and Y) to 0.7 (Z) metres.

The air photos with a scale of 1:31,680 were orthorectified to produce 64 cm resolution orthophotos. Depending on the amount of overlap, image margins were cropped to remove approximately 25% from each image. Flight lines with low side overlap (<20%) resulted in some colour/tone variations where vignette effect (darker image corners) or specular reflections (e.g., off water) could not always be removed.

Orthorectified photos were reviewed on screen at a scale of 1:10,000 to check the positional accuracy, then adjacent images were mosaiced together using ArcGIS (v10.4.1) software. The historical orthomosaic was produced using automated colour balancing to match the colour of adjacent images, applying the dodging algorithm. The completed orthomosaic was then split into single township tiles and populated with metadata. An index maps of the historical orthomosaic tiles is attached as Appendix A.

The aerial triangulation (AT) data were created using PHOTOMOD (v6 Lite x64) software in conjunction with recent July 2018 aerial imagery, which was used to identify GCP locations. The bundle block adjustment was run in multiple iterations until acceptable residuals on ground controls were achieved. No self-calibration process was required during the aerial triangulation bundle block adjustment. The overall accuracy can be estimated by using the sigma naught value, which was 0.580. The elevation values calculated during the AT process are referenced to the CGVD28 datum. Additional information pertaining to the accuracy of AT data is provided in Table 2. The processed historical aerial imagery and associated AT data were then used to create stereomodels using ApplicationMaster (v7.02.49920) within Trimble Inpho software.

Table 2: Aerial Triangulation Accuracy

	X	Y	Z	Exy (m)
GCP RMSE:	0.703	0.783	0.314	1.052
Tie Point RMSE (on images):	0.008	0.008	N/A	0.011
Sigma naught:	**0.580**			

3.0 RESULTS

Each tiled orthomosaic was reviewed on-screen at a scale of 1:10,000 with additional spot checks at a scale of 1:5,000. The positional accuracy of historical imagery was assessed by measuring the positional offset to the same feature as captured in the July 2018 Upper Red Deer River aerial imagery. In some cases where roads and land use had changed significantly, it was necessary to check the accuracy using the locations of residential homes, farm buildings and natural terrain features. Continuous features such as roads, railways and streams were checked for continuity between adjacent images. An example of the historical and modern imagery alignment is shown in Figure 1.

All the tiles in the orthomosaic were found to be accurate within 6 m at least 90% of the time, when stationary features free of modifications were measured. Errors may exceed 6 m in areas with steep or complex terrain.

The automated colour balancing used to produce the orthomosaic was not able to completely minimize the appearance of seams between images. Some areas, especially at the downstream end of the study area, were particularly problematic to correct because the dark corners of the images could not be cropped away (due to low side overlap). In other instances, the existing photogrammetric stretch (inherent in the source data) created oversaturated and overexposed areas, which were problematic to correct via automated means.

Figure 1: Example of an Orthomosaic Quality Assurance Check at 1:5,000 scale. The historical 1962/1963 orthomosaic (greyscale on left) is peeled back to reveal the modern landscape (colour image on right).

Golder undertook a completeness and quality assurance check of the AT data provided by Tarin to ensure that all requested deliverables were received and that the quality of the deliverables would meet the needs of the project and conform to AEP's general specifications. A visual check was conducted on a random sample of the stereo model (external orientation) files using the Purview Extension for ArcGIS to ensure that the requested models yielded a satisfactory visual effect when viewed in 3D view software. It was not possible to check the stereo models created in other software specific formats (DATEM), but the plain text files were checked for completeness.

The number of aerial triangulation files delivered by Tarin were counted to confirm that they matched the number of processed photos with a few randomly selected files opened and visually inspected. The spatial reference of the data was also checked to ensure that all data is projected in the 3-degree Transverse Mercator (3TM) projection using the NAD83 Canadian Spatial Reference System (CSRS) datum. The attributes of the AT photo centres and orthomosaic tile index data were checked to ensure that they contained the correct information and that file naming schemas matched AEP's guidelines. Metadata files for each image were also checked for completeness in ArcCatalog® (v 10.4).

4.0 DELIVERABLES

The following files and deliverables are submitted along with this memorandum:

- Historical 1962/1963 orthomosaic covering the Upper Red Deer River study area;
- Aerial triangulation image adjustment reports for historical images; and
- Aerial triangulation (external orientation) data in plain text format, DATEM, and Purview compatible file formats.

One digital copy of the above deliverables is provided on the accompanying USB drive.

5.0 CLOSURE

We trust that the enclosed data meets your present requirements. If you have any questions or require additional details, please contact Peter Thiede at (403) 216-8935.

Yours truly,

GOLDER ASSOCIATES LTD.

Prepared by:

ORIGINAL SIGNED BY

Peter Thiede
Senior GIS Analyst

Reviewed by:

ORIGINAL SIGNED BY

Wolf Ploeger, Dr.-Ing.
Associate, Senior River Specialist

PT/WP/pls

https://golderassociates.sharepoint.com/sites/16980g/technical work/08_channel stability investigation/03_reporting/historic image memo/rev0/1783057-51-tm-rev0 historical-imagery_20190720.docx

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APPENDIX A

1962/1963 Orthomosaic Index Map

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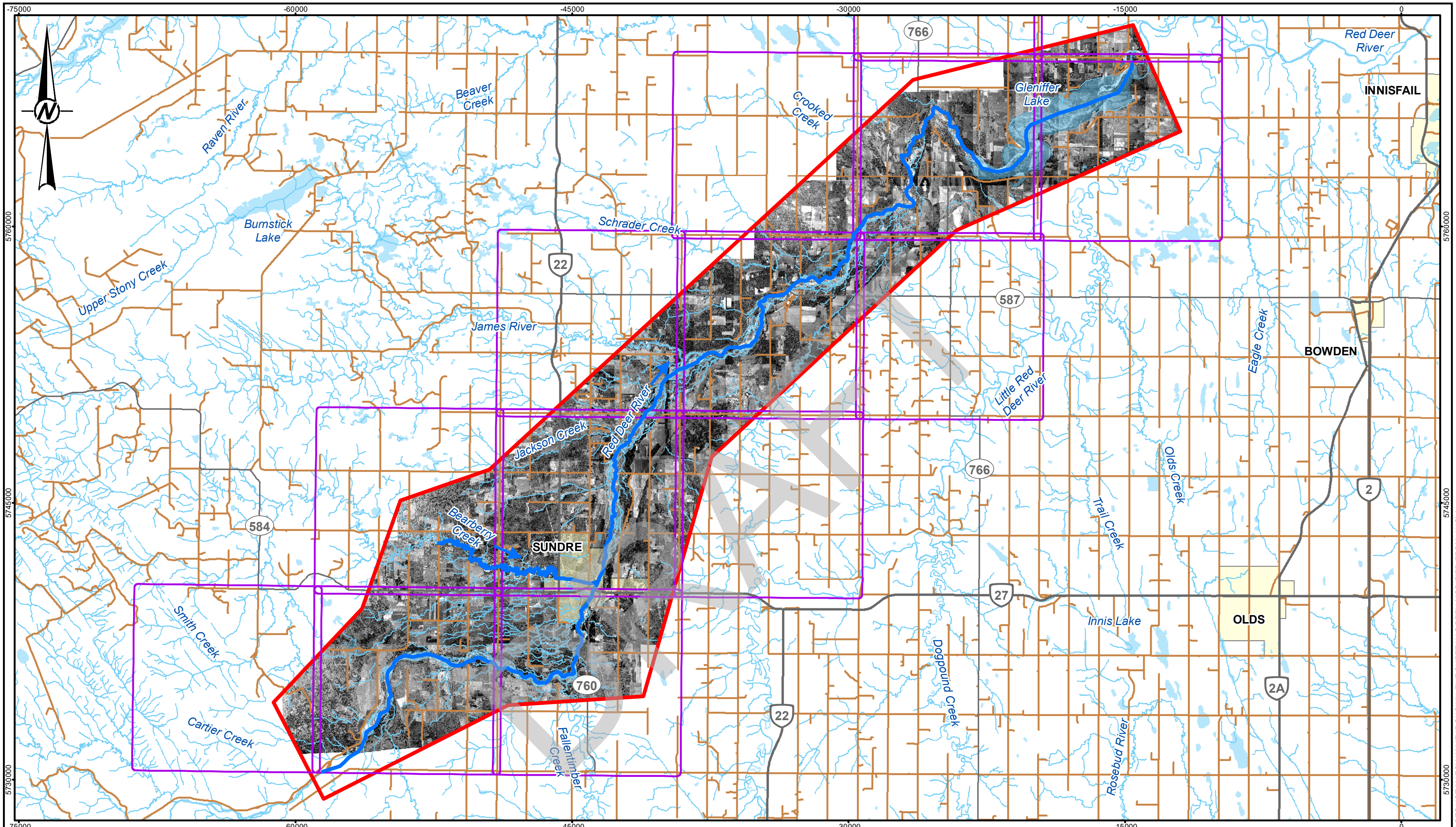

IF THIS MEASUREMENT DOES NOT MATCH WHAT IS SHOWN, THE SHEET HAS BEEN MODIFIED FROM: ANSI A

25mm

LEGEND

- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- LOCAL ROAD
- FLOW DIRECTION
- WATERCOURSE
- WATERBODY
- POPULATED PLACE
- STUDY REACH
- RIVER HAZARD STUDY AREA
- ORTHOPHOTO TILE

0 5 10

1:300,000 KILOMETRES

REFERENCE(S)

POPULATED PLACES AND HYDROGRAPHY OBTAINED FROM ALTALIS, © GOVERNMENT OF ALBERTA 2017. ALL RIGHTS RESERVED. ROADS OBTAINED FROM GEOGRATIS, © DEPARTMENT OF NATURAL RESOURCES CANADA. ALL RIGHTS RESERVED. 64 CM ORTHOMOSAIC PRODUCED FROM IMAGES ACQUIRED BETWEEN JULY 18, 1962 AND JULY 14, 1963.
DATUM: NAD 83 CSRS PROJECTION: 3TM 114

CLIENT
ALBERTA ENVIRONMENT AND PARKS

PROJECT
UPPER RED DEER RIVER HAZARD STUDY

CONSULTANT

GOLDER

YYYY-MM-DD	2019-07-20
DESIGNED	WP
PREPARED	PT
REVIEWED	RA
APPROVED	WP

TITLE
1962/1963 ORTHOMOSAIC INDEX MAP

PROJECT NO.	CONTROL	REV.	FIGURE
1783057	8000	0	1

Classification: Public

golder.com